AEDC-TDR-62-55

INITIAL AERODYNAMIC CALIBRATION RESULTS FOR THE AEDC-PWT 16-FT SUPERSONIC TUNNEL

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Propulsion Wind Tunnel Facility
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TECHNICAL DOCUMENTARY REPORT NO. AEDC-TDR-62-55

March 1962

(Prepared under Contract No. AF 40(600)-800 S/A 24(61-73) by ARO, Inc., contract operator of AEDC, Arnold Air Force Station, Tennessee)

ARNOLD ENGINEERING DEVELOPMENT CENTER

AIR FORCE SYSTEMS COMMAND

UNITED STATES AIR FORCE

NOTICES

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ARO Project Numbers 240204 and 245903

ABSTRACT

Initial aerodynamic calibration of the testing region of the PWT 16-Ft Supersonic Tunnel consisted of surveys of a twenty-foot length of nozzle and test section in which the most desirable model locations occur. These surveys were obtained with an eight-foot traversing rake utilizing pitot-wedge and pitot-temperature probes. The data obtained from these surveys included isentropic-nozzle Mach number distributions both on and off the centerline, true local Mach number determined from the pitot-wedge probes, nozzle pressure recovery, and flow misalignment. These surveys were conducted at nozzle Mach numbers of 1.50, 1.60, 1.75, 2.00, 2.25, 2.50, 2.75, 3.00, 3.25, and 3.50. Results show that maximum Mach number variations over the surveyed length are ±0.02. The stagnation pressure recovery through the nozzle, for the range of specific humidity obtained during this program, varied from 0.993 at N_m = 1.50 to 0.961 at N_m = 3.50.

CONTENTS

ILLUSTRATIONS

NOMENCLATURE

h_n	Pitot-probe height above nominal wedge surface, ft
M_1	Mach number as determined from pitot-wedge measurements
$\bar{M}_1$	Average test section centerline Mach number as determined from pitot-wedge measurements
$M_{1,i}$	Mach number from a pitot measurement for an isentropic nozzle
M_R	Mach number calculated from the retractable probe pitot pressure measurement and the nominal nozzle pressure recovery curve
N_M	Nozzle contour number
p_t	Stagnation pressure, psf
p_t'	Pressure measured by a pitot tube in supersonic flow, psf
$(p_{t,1}/p_{t,0})_{av}$	Average nozzle pressure recovery from pitot-wedge surveys obtained on the centerline and four feet above, below, east, and west of the centerline
R/ℓ	Unit Reynolds number, $R/\ell = \frac{V}{\nu}$, ft^{-1}
T_t	Stagnation temperature, °F
V	Velocity, ft/sec
X	Density ratio across an oblique shock, $X \equiv \rho_2/\rho_1$
x_ϵ	Distance from the wedge vertex (measured along the equivalent wedge surface) to the influence point governing the wave angle that is traversed by the streamline entering the pitot tube behind the oblique shock, ft (see further explanation in Appendix)
γ	Ratio of specific heats
$\Delta\alpha$	Vertical flow-misalignment angle (up-flow is positive), deg
$\Delta\psi$	Lateral flow-misalignment angle (looking upstream, cross flow to the right is positive), deg
δ_c	Wedge semi-angle after boundary layer correction, deg

δ_g	Geometric wedge semi-angle, deg
δ_n	Nominal wedge semi-angle, deg
δ^*	Boundary layer displacement thickness, ft
ϵ	Boundary layer flow-deflection angle, deg
θ_c	Bow-wave angle calculated using δ_c, deg
ν	Kinematic viscosity, ft^2/sec
ρ	Air density, $slugs/ft^3$
σ	Specific humidity of the tunnel air, lb of moisture per lb of mixture

SUBSCRIPTS

0	Stilling chamber conditions
1	Free-stream conditions in the test section
2	Conditions in the test section behind the oblique shock wave generated by the wedge surface on the pitot-wedge probe
e	Conditions just outside the boundary layer

1.0 INTRODUCTION

The PWT 16-Ft Supersonic Tunnel is composed of a number of complex sub-systems such as the compressor system, nozzle system, and diffuser system, each requiring extensive evaluation. As the various components of the tunnel were completed, calibration work was begun to evaluate the operational characteristics of the components. The first major component of the tunnel to become operational was the compressor system. Operation and calibration of the compressor began in February of 1960 and was continued until mid 1960. At this time the flexible nozzle system was ready for evaluation and this work was carried out along with some additional compressor evaluation. By the latter part of 1960, the equipment for the aerodynamic calibration of the test section and nozzle was completed and ready for installation, and the variable geometry diffuser was ready for operation, although not calibrated. Actual calibration of the nozzle and test section was begun in December, 1960.

The equipment provided for obtaining aerodynamic calibration data was designed to survey the nozzle and test section in 11-ft segments, requiring re-positioning of the probe in the test section as the change was made from one segment to the next. Five probe positions were required to evaluate the flow conditions throughout the complete testing region. However, after two segments had been surveyed, operational difficulties with the nozzle control system caused the nozzle to be made inoperable for a considerable period of time, and calibration work was terminated until such time as it could be worked into the testing schedule. The two segments of the test section and nozzle which were surveyed represent a twenty-foot length which contains the most desirable model locations. The calibration data presented in this report define the flow conditions in this testing area. When additional calibration work is carried out, supplemental results will be compiled.

2.0 APPARATUS

2.1 BASIC TUNNEL

The PWT 16-Ft Supersonic Tunnel is a continuous-flow, closed-circuit wind tunnel designed to operate at stagnation pressures of approximately 100 to 2000 psfa. Compressor power is provided by a four-motor electric drive system delivering a maximum of 216,000 horsepower.

Manuscript released by authors February 1962.

Temperature control is provided by air-to-water heat exchangers located upstream and downstream of the compressor. The flexible nozzle provides contours for generating supersonic flow at Mach numbers from 1.50 to 5.00. The removable test section is 40 ft long with a 16 by 16 ft cross section. The diffuser side walls are adjustable to provide the flexibility required to set the optimum starting and running configurations. A scavenging scoop is provided in the diffuser to remove products of combustion during propulsion tests. A closed tip was installed on this scoop during this calibration. The location of the tunnel and its relationship to the remainder of the PWT area is shown in Fig. 1.

2.2 COMPRESSOR

The compressor system is made up of four axial-flow compressor units or cylinders arranged so that they may be operated with either one, two, three, or four cylinders in series. This flexibility of operation is made possible by the use of iris valves which provide for the air emerging from one cylinder to either enter or by-pass the succeeding cylinders, with remotely controlled couplings to allow the idle cylinders to be disconnected from the drive system. The use of a compressor system of this type was dictated by the wide range of pressure ratio and volume flow requirements for operating the tunnel at Mach numbers from 1.50 to 5.00. The first three cylinders are four-stage compressors with adjustable inlet guide vanes and stator blades. The fourth cylinder is a six-stage compressor with manually adjustable blading. The overall range of pressure ratio available is approximately 1.1 to 8.0.

2.3 FLEXIBLE NOZZLE

The 92-ft-long flexible nozzle is adjusted by 29 pairs of hydraulically powered, ball-bearing jack actuators controlled by a digital-computer-type control system using a magnetic tape memory. Three-hundred basic contours are provided to cover the Mach number range from 1.50 to 4.50 in increments of 0.01, with provisions for aerodynamic corrections when required. This same provision makes possible the extension of the range of control from M = 4.50 to 5.00. The supersonic portion of the nozzle is approximately 65 ft in length and is controlled by 19 pairs of jacks with spacings of three and four feet. The flexible wall position is measured at each jack station by means of tape-reel sensing devices attached to a water-cooled reference frame. These measurements are fed into the control system for use in changing from one contour to another and for maintaining a selected contour within ±0.035 inches of the calculated contour, with a repeatability of ±0.008 inches.

Twenty design contours, covering the Mach number range from 1.5 to 5.0, were calculated for the flexible nozzle by the designer, Sandberg-Serrell Corporation. The calculation procedure utilized the continuous third derivative concept and is described fully in Ref. 1. Boundary layer corrections were applied using the method described in Ref. 2, based on mean values of Reynolds number. In calculating the nozzle plate shapes and jack settings necessary to produce these contours, the wall temperature becomes important in that it affects the plate length and jack spacing. The expected range of operating temperatures was studied, and mean values were selected for use in the nozzle calculations. In these calculations it was assumed that the plates were subjected to these temperatures uniformly. These values varied linearly with Mach number from 140°F at $N_M = 1.5$ to 375°F at $N_m = 3.0$, with 375°F being used above $N_M = 3.0$. Once the twenty design contours had been defined, interpolations were carried out using the best mathematical procedures available to provide contours at every 0.01 in Mach number.

2.4 TEST SECTION

The removable 16 by 16 by 40 ft test section is made up of two carts, each 20 ft in length, which can be arranged with either cart in the front or rear position. A third cart is provided to allow more rapid changes from one type of model support system to another. A sting support system is installed in one cart, a vertical pitch table in a second, and a sidewall balance is to be installed in the third. These latter two installations can be faired over to allow either of these carts to be used as an empty cart in conjunction with one of the other support systems. For the calibration work reported here, the calibration probe was installed in one of these carts, installed in the forward position, with an empty cart in the rear position.

The air-side surfaces of these carts are made up of stainless steel panels, with inserts provided for water-cooled enclosures for lighting, television, and motion picture camera installations. The top and bottom test section walls are permanently set 16 ft apart and parallel. The side walls can be converged or diverged either as straight 40-ft walls extending the full test section length, or as 20-ft panels, allowing different convergence or divergence for the front and rear carts. For the calibration work presented here, the side walls were diverged 28 minutes throughout the test section.

2.5 VARIABLE GEOMETRY DIFFUSER

The diffuser system is composed of a variable geometry diffuser of rectangular cross section approximately 100 ft in length followed by a fixed diffuser which also includes the transition from rectangular to circular cross section. The variable geometry diffuser has fixed, parallel top and bottom walls spaced 16 ft apart, and movable side walls made up of five straight sections hinged together. The upstream section is approximately 24 ft long, followed by panels of 20, 16, and 16 ft, while the downstream section is approximately 24 ft long with a sliding joint to provide the change in length required as the side walls are moved to different positions. By the use of hydraulic actuators, the diffuser-to-test section area ratio can be increased to allow supersonic flow to become established, and can then be decreased to improve the diffuser efficiency, allowing a reduction in the tunnel pressure ratio required to maintain supersonic flow.

2.6 CALIBRATION EQUIPMENT

The device selected for the air-flow calibration of the testing region of the test section and nozzle was a strut-supported traversing probe utilizing an eight-foot rake with nine instrumentation sockets one foot apart. This rake is shown in Fig. 2. Because of the usual compromises between strength and blockage, the length of travel of the rake actuator was limited to eleven feet. As a result, four probe locations in the test section plus a 10-ft probe extension were required to survey the desired length of approximately 50 ft. This extension was limited to one instrumentation socket only, on the tunnel centerline.

Four basic types of data were desired from the calibration probe surveys; these were test section Mach number, flow angularity, and stagnation temperature distributions and nozzle stagnation pressure recovery. Two types of probes were provided to fit the rake instrumentation sockets to obtain these measurements. The simplest of these, a pitot pressure and stagnation temperature probe, combined a single pitot tube and a Rosemount Model 103-3 high-response triple-shielded precision thermocouple in one probe assembly. Unfortunately, the life of these thermocouples proved to be quite short because of particle bombardment in the tunnel, resulting in broken wires at the measuring junction. As a result, very little valid temperature data were obtained with these probes.

The second type of probe designed for use on the rake was the pitot-wedge probe. In using this probe, pitot-pressure measurements were made ahead and behind a shock wave originating from the leading

edge of a precision wedge of known geometric angle. An iteration process, described in the Appendix, made it possible to calculate the effective wedge angle and the true local Mach number from these pitot measurements, and once this is known, the nozzle stagnation pressure recovery could be determined. Static pressure orifices on the wedge surfaces provided a means of measuring local flow angularity after the wedge sensitivity had been calibrated in another wind tunnel. Because of the relationship between wedge angle and wave angle as a function of Mach number, a fixed-geometry pitot-wedge probe can be used only for a limited range of free-stream Mach numbers. To cover the range of Mach numbers required for this calibration, probes were fabricated with nominal wedge half-angles of 7, 10, and 20 deg. The pertinent dimensions for these probes are shown in Fig. 3.

Pressure leads from the probe sockets were routed to a water-cooled instrument compartment installed in the actuator boom, where the pressures were measured by means of differential pressure transducers, referenced to a nozzle static pressure near the throat. Solenoid valves in the compartment allowed remote switching of pressure connections to check on transducer calibrations and zero shifts. Thermocouple leads from the rake sockets were routed directly to instruments outside the tunnel along with the electrical leads from the transducers.

A retractable probe, shown in the upper portion of Fig. 2 in the extended position, was provided at Sta. -12.9 in the nozzle ceiling as a permanently installed tool for checking the nozzle Mach number. Normally flush with the nozzle wall to provide no disturbance to the airflow, this probe could be extended approximately 30 inches to obtain a pitot pressure measurement. This probe could also be set to any desired position between its limits, providing a means of measuring the boundary layer profile at this location.

In order to evaluate the data obtained during this calibration, it was important to know the specific humidity of the air in the tunnel. A General Electric frosting-mirror dew point indicator was the primary instrument used for humidity measurements, using a sampling line connected to the stilling chamber upstream of the nozzle. An Alnor dew point indicator was occasionally used for comparative purposes.

A limited number of wall static pressure orifices were provided in the nozzle, test section, and variable geometry diffuser. These were connected to manometers in the control room using Unity oil and TBE as measuring fluids. Although these boards were photographed as a matter of record, their primary purpose was to aid in monitoring flow establishment and breakdown. Because of the slow response of the manometer display, caused by the distance involved and the low pressures to be measured, a more responsive indication of diffuser flow

conditions was desired. This was provided by installing twelve transducer assemblies in the diffuser at approximately 4-ft intervals. These assemblies were designed so that one side of the transducer was vented to a high-response orifice in the diffuser wall, while the other side was highly damped. By viewing the transducer outputs on a dynamic monitor, incipient flow-breakdown could be detected, and steps could be taken to prevent it.

All of the instrumentation inputs defining tunnel conditions and calibration measurements were fed into the ERA 1102 digital computer through the permanent data-handling system. Parameters which were needed immediately for test-monitoring were calculated on-line and tabulated and plotted in the control room. Inputs required for the more elaborate calculations were punched on tape and furnished to the IBM 7070 digital computer for off-line calculations.

3.0 PROCEDURE

3.1 TUNNEL OPERATION

During this calibration period, two-, three-, and four-cylinder compressor configurations were utilized in operating at nozzle settings from 1.50 to 3.50. Supersonic flow was established at relatively low stagnation pressures, and the variable geometry diffuser was then adjusted to a more efficient operating contour, allowing tunnel pressure ratio to be reduced. Only a limited amount of time was available for evaluating diffuser performance, and hence the settings used during this period do not represent optimum use of this diffuser. In general, the diffuser was evaluated only to the extent required to obtain the test section conditions desired for calibration. Once flow was established and the diffuser set, tunnel pressure was set to the desired value, and the tunnel humidity was reduced as much as possible before the calibration surveys were begun.

3.2 CALIBRATION PROCEDURE

In the calibration period during which the data reported herein were obtained, the traversing probe assembly was installed in two test section locations, surveying the test area from Tunnel Station +1 in the test section to Tunnel Station -19 in the nozzle. The same basic procedure was followed in obtaining data at both locations. The rake configuration selected had pitot-wedge probes installed in the center and two outboard

sockets, with six pitot-temperature probes in the remaining six sockets, (see Fig. 2). The wedge angle of the installed pitot-wedge probes was selected to match the range of Mach numbers to be surveyed; at some Mach numbers it was possible to use either of two wedges, and both were used as often as possible to obtain correlation data. The majority of the calibration data were obtained with the rake vertical, although some data were obtained with the horizontal configuration. Likewise, the wedges were oriented vertically for most of the testing, measuring lateral flow-angle deviations. This orientation was selected because, with a nozzle having contoured side walls, it was felt that the greater flow-angle deviations would occur in this plane.

Attempts were made to obtain calibration data at pressure levels of 250, 500, and 1000 psf. Results at 250 psf were discouraging because of instrumentation inaccuracies and the inability to maintain the desired specific humidity. Reasonable results were obtained at 500 and 1000 psf, with 1000 psf preferred because of increased instrumentation accuracy.

Once flow had been established, the pressure level set, and a satisfactory humidity level had been achieved, a calibration survey was made by extending the traversing probe in increments of 0.5 feet, with a short pause after each movement to allow the pressure instrumentation to stabilize. After taking data at the fully extended position a check point was obtained at the fully retracted position to check for instrumentation drift. In addition to the traversing probe data, additional data points were obtained at both ends of the survey with the retractable probe fully extended.

Surveys of the type described above were obtained at nominal nozzle Mach numbers of 1.50, 1.60, 1.75, 2.00, 2.25, 2.50, 2.75, 3.00, 3.25, and 3.50. At the time of this calibration, Mach numbers above 3.50 could not be achieved with any great degree of success. (Subsequent study of the diffuser performance has resulted in the achievement of Mach numbers up to 4.0, but no calibration data have been obtained at these conditions.)

3.3 DATA REDUCTION PROCEDURE

Two digital computers were used for the data reduction program. An ERA 1102 was utilized for on-line calculations, while an IBM 7070 was utilized for the more time consuming calculations which were carried out off-line. Conversion of pressure and temperature measurements into standard engineering units was accomplished in the conventional manner using predetermined instrument calibration data. The

more complex calculations involving Mach number are explained below.

An approximation to the normal-shock adiabatic flow relationship

$$\frac{p_{t,0}}{p'_{t,1}} = \left(\frac{M_{i,1}^2 + 5}{6M_{i,1}^2}\right)^{7/2} \left(\frac{7M_{i,1}^2 - 1}{6}\right)^{5/2}$$

was used to calculate the isentropic nozzle Mach number determined by each pitot-pressure measurement. This approximation requires less computer time for solution than the exact relationship and has a Mach number error of less than 0.001. The approximation is as follows:

$$M_{i,1} = \frac{-\left[a_0 + a_1\left(\frac{p_{t,0}}{p'_{t,1}}\right) + a_2\left(\frac{p_{t,0}}{p'_{t,1}}\right)^2 + a_3\left(\frac{p_{t,0}}{p'_{t,1}}\right)^3 + a_4\left(\frac{p_{t,0}}{p'_{t,1}}\right)^4\right]}{b_0 + b_1\left(\frac{p_{t,0}}{p'_{t,1}}\right) + b_2\left(\frac{p_{t,0}}{p'_{t,1}}\right)^2 + b_3\left(\frac{p_{t,0}}{p'_{t,1}}\right)^3 + b_4\left(\frac{p_{t,0}}{p'_{t,1}}\right)^4}$$

The constants for this equation are given below:

$a_0 = 1.001610 \times 10^{0}$	$b_0 = 1.559619 \times 10^{-1}$
$a_1 = -3.650460 \times 10^{0}$	$b_1 = 8.774662 \times 10^{-1}$
$a_2 = 1.911036 \times 10^{0}$	$b_2 = -1.042554 \times 10^{0}$
$a_3 = 9.538176 \times 10^{-1}$	$b_3 = -1.693207 \times 10^{-1}$
$a_4 = 0$	$b_4 = 1.221138 \times 10^{-3}$

These constants are valid for the Mach number range from 1.45 to 4.00.

The true local Mach number was obtained from pitot-wedge probe measurements using an iteration procedure which is outlined in the Appendix. When the true local Mach number is known, the nozzle stagnation pressure recovery can be obtained from the relationship below:

$$\left(\frac{p_{t,1}}{p_{t,0}}\right) = \left(\frac{M_1^2 + 5}{6M_1^2}\right)^{7/2} \left(\frac{7M_1^2 - 1}{6}\right)^{5/2} \left(\frac{p'_{t,1}}{p_{t,0}}\right)$$

4.0 RESULTS AND DISCUSSION

The results obtained during the calibration program are presented in the form of axial distributions of Mach number and flow misalignment and in the form of calibration parameters required in order to utilize the results for normal test-data reduction programs. In presenting the axial distributions, data obtained at the two different probe positions are distinguished by the use of different symbols, making possible a comparison in the overlap region between tunnel stations -8 and -10. Variations

of the true local Mach number, calculated from pitot-wedge probe measurements along the tunnel centerline, are shown in Fig. 4. These distributions show maximum variation of ±0.02 in Mach number over the twenty-foot length surveyed. In most cases, agreement in the overlap regions was quite good. Figure 5 presents corresponding distributions of the Mach numbers which are obtained if nozzle pressure losses are neglected, in which case the Mach number can be determined from the ratio of measured pitot pressure in the test section to stilling chamber pressure. The Mach numbers determined in this manner are slightly higher than those determined from the pitot-wedge probe measurements, because of the neglected pressure loss, but provide a basis for comparison of the off-centerline measurements obtained with simple pitot tubes.

Figures 6 and 7 present off-centerline Mach number distributions obtained with the eight-foot rake oriented both vertically and horizontally. The data presented are typical of those obtained throughout the Mach number range of the investigation and show maximum variations of ±0.01 in Mach number over the eight-foot span of the rake.

Figure 8 presents the results of flow misalignment measurements at the tunnel centerline with the wedge oriented to sense flow angle variations in the lateral direction. The largest variations over the surveyed length, as well as the largest average misalignment, occurred at the lowest Mach numbers, with gradual decreases in both quantities as Mach number was increased. At a nozzle setting of 1.50, the average misalignment was 0.70 deg with variations of ±0.50 deg, while at 3.50, the average misalignment was 0.15 deg with variations of ±0.10 deg over the surveyed length.

Because this calibration program was terminated prior to completion, the results of the off-centerline flow misalignment measurements are incomplete; those measurements which were obtained are shown in Fig. 9. Measurements of the lateral flow misalignment angle, $\Delta\psi$, made east and west of the tunnel centerline (Figs. 9a and b) show that the flow quality on the west side did not differ greatly from the centerline measurements except for more noticeable gradients at the higher Mach numbers, while on the east side the measurements at nozzle settings of 2.75 and below showed large deviations and large average values of misalignment. The average misalignment increased as the Mach number was decreased, approaching four degrees at a nozzle setting of 1.50. Figures 9c and d show $\Delta\psi$ measurements obtained above and below the tunnel centerline, where the values are similar to those measured at the centerline. Only two surveys were made in which $\Delta\alpha$, the vertical misalignment, was measured. These were obtained at reduced stagnation pressure, when the instrumentation sensitivity was marginal, but showed that the average misalignment in this plane was near zero at the two Mach numbers surveyed.

In examining the flow misalignment results, two areas of concern were noted. First, measurements at the tunnel centerline indicated that the average misalignment as well as the axial variations increased as the nozzle Mach number was decreased. Secondly, measurements obtained four feet east of the centerline indicated a rapid deterioration of flow quality in this region below a nozzle setting of 2.75. Two physical characteristics of the nozzle probably contribute to these problems. As the nozzle Mach number is reduced, the length of the shock cancellation region of the contour decreases, resulting in fewer jacks available to shape this critical portion of the nozzle. This probably contributes to the centerline variations at the lower Mach numbers. A probably more predominant factor both on and off the centerline is the decrease in contraction ratio as the nozzle Mach number is reduced. This decrease in contraction ratio allows the flow conditions ahead of the nozzle throat to have increasing influence on the flow downstream of the throat. It is possible that a flow problem resulting from the corner just upstream of the nozzle may be the source of the large lateral flow misalignment measured east of the centerline, and study of this possibility is underway.

The average centerline pitot-wedge Mach number, $\overline{M}_1$, resulting from each of the nozzle contours surveyed during this calibration, was related to the nozzle contour number, N_M, by using the difference, $(N_M - \overline{M}_1)$, as the primary calibration parameter. Since the nozzle contours represent a family of associated shapes, the variation of this parameter with nozzle contour number should be a continuous function. Figure 10 presents a summary of the Mach number calibration results obtained during this investigation and the faired curve selected to represent these results in reducing future test results. The symbols used show the probe positions, rake orientations, and wedge half-angles used in obtaining these results and also distinguish between the results obtained at normal stagnation temperatures of 200 to 300°F and those obtained using the high stagnation temperature range of 250 to 650°F.

The ratio of the total pressure in the test section to an average static pressure in the stilling chamber, called the nozzle pressure recovery, is shown in Fig. 11 as a function of the nozzle contour number. The loss in total pressure between the stilling chamber and the test section is caused by an accumulation of unavoidable nozzle imperfections and condensation effects resulting from the specific humidity conditions during this investigation. In addition to these losses, the pressure recovery also reflects the small total pressure error caused by the difference between the average stilling chamber total pressure and the average stilling chamber static pressure which is used as a basic input for operation of the wind tunnel. The symbols used are the same as in Fig. 10 and have previously been explained. The faired

curve selected for use in future data evaluation is shown, giving a pressure recovery which varies from 0.993 at N_M = 1.50 to 0.961 at N_M = 3.50. As a result of the scatter which may be observed in the test results, it is felt that the use of this curve will result in an uncertainty in pressure recovery of ±1 percent.

Figure 12 presents the relationship between the Mach number calculated from the retractable pitot-probe measurement, the nominal nozzle pressure recovery, and the average centerline Mach number determined from the pitot-wedge probe. The parameter (M_R - $\overline{M}_1$) can be used in predicting the true Mach number from retractable probe measurements during future tests.

All of the calibration data presented were obtained at a tunnel stagnation pressure of 1000 psf, which was selected because of the instrumentation inaccuracies at lower pressures. Sufficient data were obtained at a stagnation pressure of 500 psf to indicate that the changes in calibration parameters caused by changing the tunnel pressure level were small enough to be within the previously quoted uncertainties in these parameters.

Early in this calibration program, the effects of varying the tunnel specific humidity were investigated. It was found that as σ_o was reduced by an order of magnitude from 0.01 to 0.001, noticeable increases were obtained in the nozzle pressure recovery and the measured pitot-wedge Mach number at a given nozzle contour. These early studies indicated that there was a limiting value of σ_o near 0.001 (decreasing slightly with increasing Mach number), below which the effects of σ_o changes were almost negligible. Based on this information, the calibration data were obtained at the specific humidity levels shown in Fig. 13. Because these values of σ_o approach the limit of the tunnel drying capability, the scatter shown in Fig. 13 was a result of the day to day drying capability. The calibration results presented in this report represent the conditions which will exist in the test section when the specific humidity is in the range shown in Fig. 13. Subsequent studies have shown that the calibration parameters will change slightly at lower values of σ_o, and as shown earlier, will have substantial changes at increased values of σ_o. Further investigation would be required to evaluate the calibration parameters throughout the range of values of σ_o which might be encountered in tests where adequate drying could not be provided.

Figure 14 shows the variation of stagnation temperature with nozzle setting during this calibration, as determined from a grid of thermocouples installed on the upstream side of the turning vanes in the corner ahead of the nozzle. Two temperature ranges were investigated. The lower range represents the normal tunnel operating range during this

period and represents the temperature level made necessary by the requirement to match the compressor to the tunnel resistance line. The upper temperature range is typical of that required for simulation of temperatures encountered in the atmosphere. Below Mach number 2.0, low and high temperature settings were essentially the same.

Figure 15 presents the unit Reynolds number variation with nozzle setting during calibration, based on 1000 psf stagnation pressure, the temperatures shown in Fig. 14, and the isentropic Mach number at the tunnel centerline. The two curves are a consequence of the two temperature ranges shown in Fig. 14.

From a study of the measuring equipment and the results obtained during this calibration, the uncertainties in the data presented were estimated for a probability of 95 percent. These uncertainties are summarized in the following table:

QUANTITY	UNCERTAINTY
$\overline{M}_1$	±0.02
$p_{t,0}$	±3 psf
$p_{t,1}/p_{t,0}$	±0.01
$T_{t,0}$	±5 °F
σ_o	±0.00005
$\Delta\psi$	±0.1 deg

5.0 CONCLUSIONS

The following conclusions can be drawn from these calibration results:

1. Maximum variations in centerline Mach number over the twenty-foot length surveyed are ±0.02.
2. Off-centerline surveys both vertically and laterally agree with the centerline surveys within ±0.01 in Mach number.
3. Lateral flow misalignment at the centerline is greatest at the lowest Mach numbers and decreases gradually as Mach number is increased, with average values of 0.70 deg at N_M = 1.50 and 0.15 deg at N_M = 3.50.

4. Off-centerline lateral flow misalignment is greatest in the region east of the tunnel centerline; further studies are required to determine the cause of this misalignment and the corrective measures required.

5. Nozzle pressure recovery decreases with increasing Mach number from 0.993 at N_M = 1.50 to 0.961 at N_M = 3.50 provided the specific humidity is maintained within the range obtained during this calibration program.

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APPENDIX

DATA REDUCTION EQUATIONS FOR THE PITOT-WEDGE PROBE

The true local Mach number was obtained from pitot-wedge probe pressure measurements using a closed loop iteration of the following equations. These equations require the assumption that the flow is adiabatic and behaves as a perfect gas with constant specific heats ($\gamma = 7/5$).

Reference 3 gives the following relationship between Mach number, wedge angle, and shock wave angle:

$$\sin^6 \theta_c + b \sin^4 \theta_c + c \sin^2 \theta_c + d = 0 \tag{1}$$

where

$$b = -\frac{M_1^2 + 2}{M_1^2} - 1.4 \sin^2 \delta_c \tag{2}$$

$$c = \frac{2M_1^2 + 1}{M_1^4} + \left(1.44 + \frac{0.4}{M_1^2}\right) \sin^2 \delta_c \tag{3}$$

$$d = -\frac{\cos^2 \delta_c}{M_1^4} \tag{4}$$

Equation (1) has been solved for θ_c, and the solution is presented in the following form:

$$\theta_c = \sin^{-1}\left\{2\sqrt{\frac{b^2 - 3c}{9}} \cos\left[\frac{4\pi}{3} + \frac{1}{3}\cos^{-1}\left(\frac{\frac{1}{3}bc - \frac{2}{27}b^3 - d}{2\sqrt{\left(\frac{b^2 - 3c}{9}\right)^3}}\right)\right] - \frac{b}{3}\right\}^{1/2} \tag{5}$$

To obtain the solution which is useful here, the boundary condition on the $\cos^{-1}$ term is that the angle must be less than π. Equation (5) represents an explicit expression for shock-wave angle as a function of Mach number and the effective wedge angle.

The effective wedge angle can be considered as the sum of the geometric wedge angle and a small equivalent boundary layer wedge angle, as follows:

$$\delta_c = \delta_g + \epsilon \tag{6}$$

To arrive at an expression for ϵ, the details of the wedge flow field must be examined closely as illustrated in Fig. A, as shown on the following page.

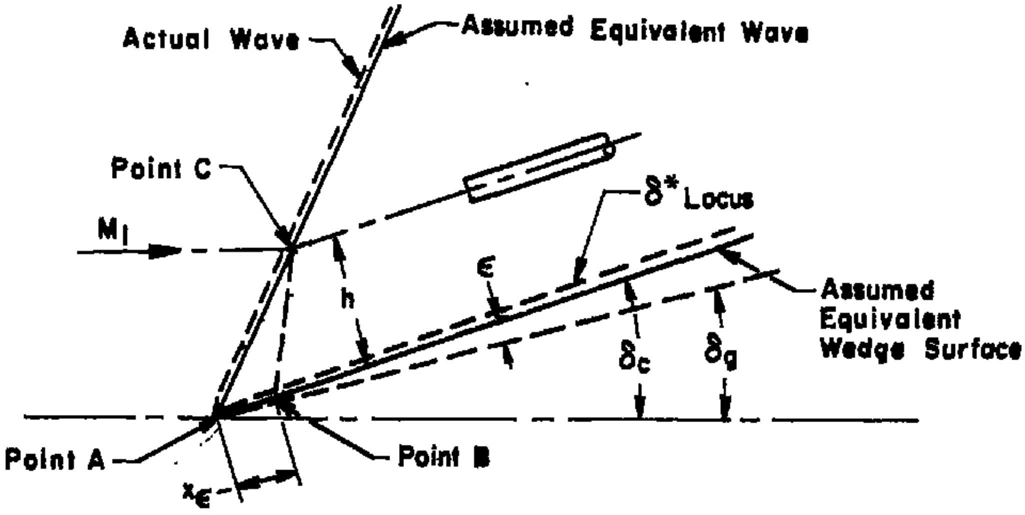


Fig. A. Details of the Wedge Flow Field

From Fig. A it is seen that the streamline entering the pitot tube behind the shock front experiences an oblique shock loss governed approximately by the effective wedge surface at point B, a distance x_ϵ downstream of the vertex, A, measured along the effective wedge surface. Since the influence of the boundary layer is a weak disturbance, the inclination of line BC to the mean flow direction behind the wave can be approximated by a Mach line. The distance from the wedge leading edge to the point B may then be defined in terms of probe geometry and Mach number by the following relationship:

$$x_\epsilon = h_n \left[\cot \left(\theta_c - \delta_c\right) - \sqrt{M_2^2 - 1} \right] \tag{7}$$

This length is used as the characteristic length in calculating the boundary layer growth on the wedge surface. The boundary layer growth is assumed to be the same as on a flat plate, based on free-stream conditions just clear of the boundary layer. An empirically determined expression for the boundary layer growth on a flat plate is given in Ref. 4 as:

$$\frac{d\delta^*}{dx} = 0.86 \left(1 + 0.277\ M_e^2\right) \sqrt{\frac{\nu_e}{x V_e}} \tag{8}$$

In order to relate the conditions clear of the boundary layer behind the shock front to the free stream, the calculations may be simplified by using the density ratio parameter X, which is defined as

$$X = \frac{\rho_2}{\rho_1} \tag{9}$$

which, for $\gamma = 7/5$, may be written as

$$X = \frac{\tan \theta_c}{\tan \left(\theta_c - \delta_c\right)} \tag{10}$$

Using Eq. (9) and other equations given in Ref. 3, the Mach number behind the wedge shock may be expressed as follows:

$$M_2 = \left(\frac{5}{6X - 1}\right)^{1/2} \csc\,(\theta_c - \delta_c) \tag{11}$$

The velocity behind the shock is given by

$$V_2 = \frac{49.02\sqrt{T_{t,0} + 459.6}\;M_2}{(1 + 0.2\,M_2^2)^{1/2}} \tag{12}$$

By expressing Eq. (8) in terms of the flow field behind the wedge shock, the following empirical relationship can be written for the boundary layer wedge angle:

$$\epsilon = \frac{49.27\,(1 + 0.277\,M_2^2)\,(\nu_2\,p_{t,1})^{1/4}}{(V_2\,x_\epsilon)^{1/4}\,\sqrt{p_{t,0}}}, \text{ deg} \tag{13}$$

Applying Sutherland's equation (see Ref. 3) for viscosity,

$$\left(\nu_2\,p_{t,1}\right) = \frac{(3.895 \times 10^{-8})\,(T_{t,0} + 459.6)^{5/2}\,(1 + 0.2\,M_2^2)^{-1/2}\,(1 + 0.2\,M_1^2)^{5/2}}{X\,[(T_{t,0} + 459.6) + (198.6)\,(1 + 0.2\,M_2^2)]} \tag{14}$$

The remaining terms have been defined in Eqs. (7), (10), (11), and (12). Since δ_g is a measured quantity, all of the quantities needed to evaluate Eq. (6) are now known.

The local pitot-wedge Mach number, M_1, is related to the ratio of the pitot-pressure measurements ahead and behind the shock, $p'_{t,1}/p'_{t,2}$, and the shock wave angle, θ_c, by the following implicit equation:

$$M_1^2 = \frac{(p'_{t,1}/p'_{t,2})^{2/7}}{\left[\dfrac{\beta^2 + 5}{\beta^2\,(M_1^2 + 5)}\right]\left[\dfrac{1}{6} + \dfrac{5\,(7\beta^2 - 1)\,(\beta^2 + 5)}{216\,M_1^2\,\beta^2 - 30\,(\beta^2 - 1)\,(7\beta^2 + 5)}\right]} \times$$

$$\frac{1}{\left\{\left[\dfrac{7\beta^2 - 1}{7M_1^2 - 1}\right]\left[\dfrac{252\,M_1^2\,\beta^2 - 35\,(\beta^2 - 1)\,(7\beta^2 + 5)}{6\,(7\beta^2 - 1)\,(\beta^2 + 5)} - \dfrac{1}{6}\right]\right\}^{5/7}} \tag{15}$$

where

$$\beta^2 = M_1^2 \sin^2 \theta_c \tag{16}$$

To solve this equation an iterative procedure was used whereby the right-hand side was successively evaluated until the difference between consecutive solutions was less than or equal to 0.000005. The square root of this solution gave the final approach Mach numbers, M_1, to an accuracy of 0.001 or better.

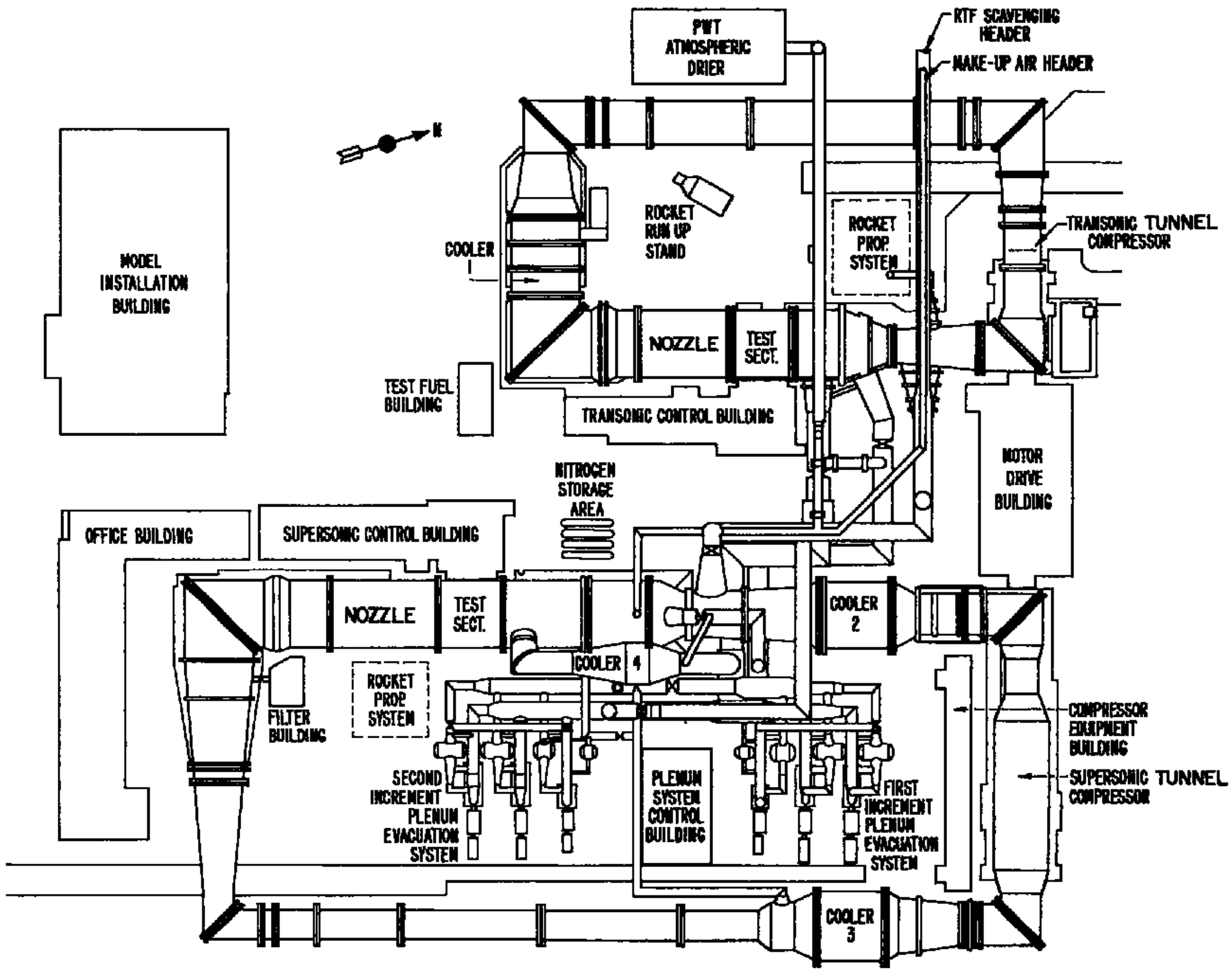
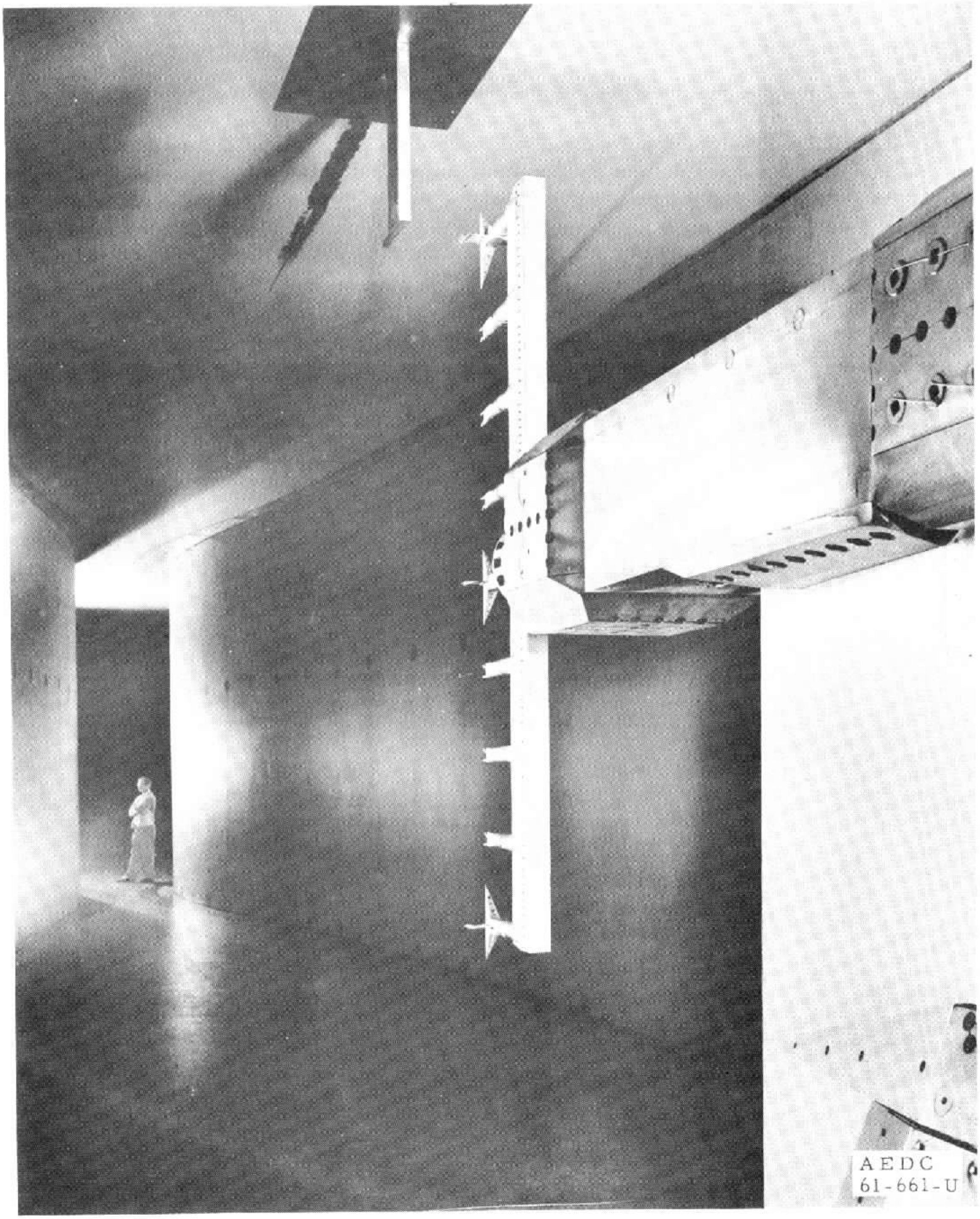
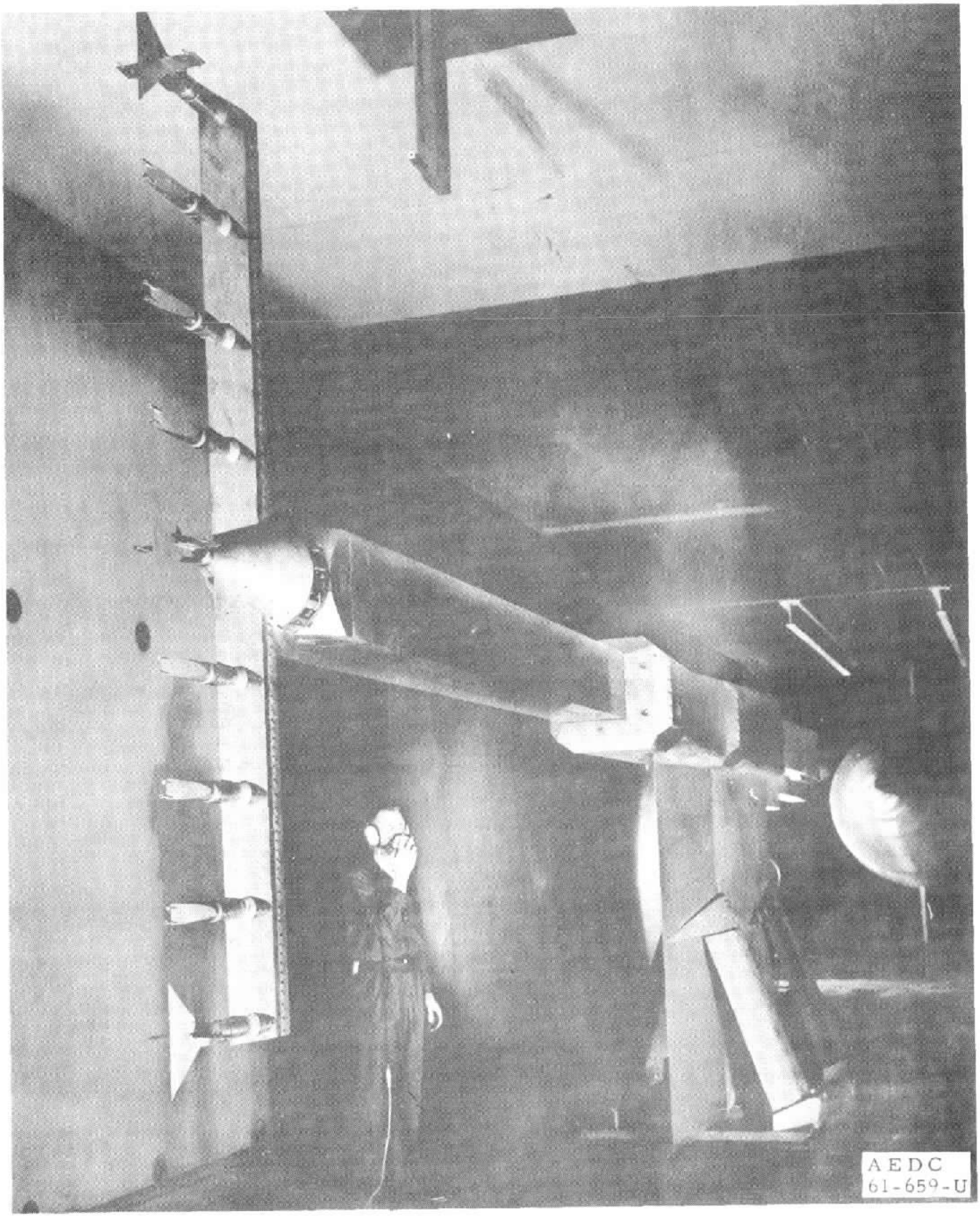


Fig. 1 Propulsion Wind Tunnel Facility



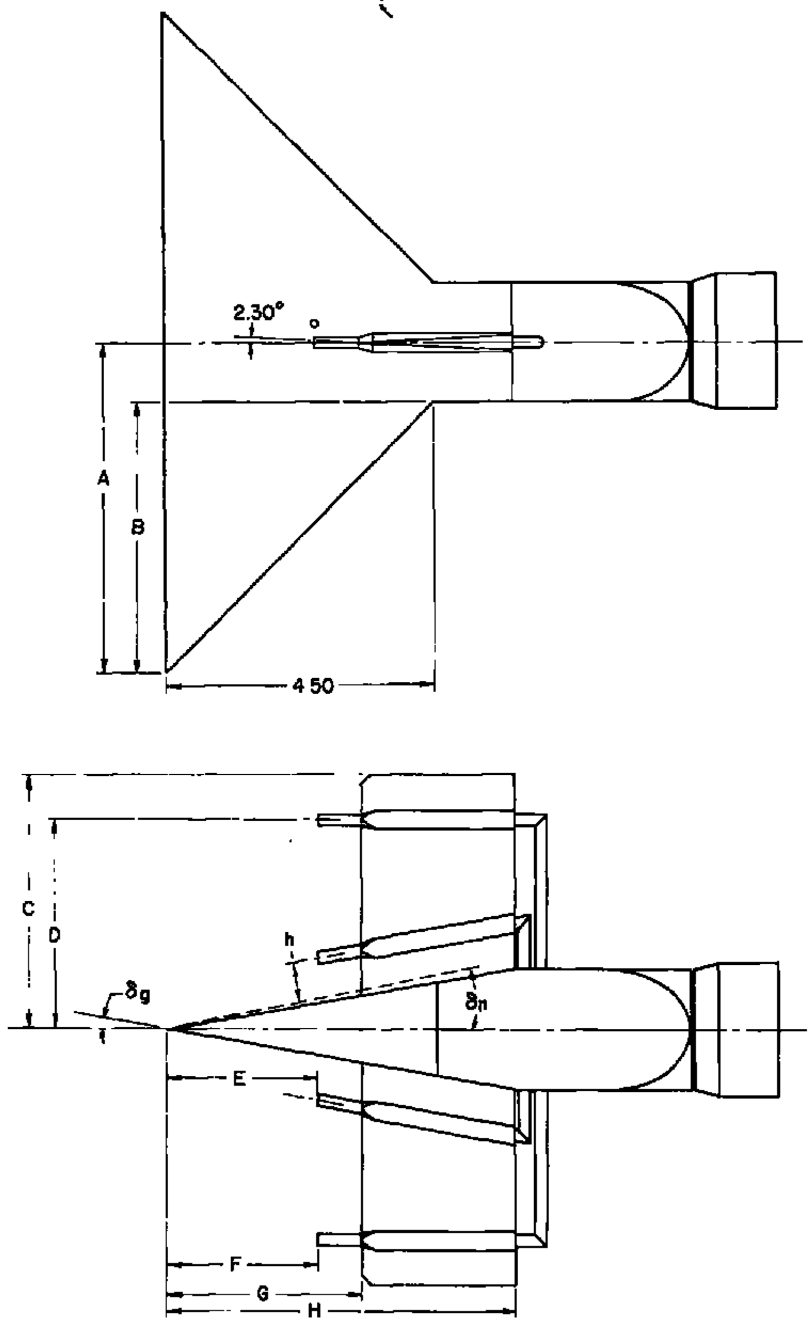
a. Upstream View

Fig. 2 Supersonic Tunnel Flexible Nozzle, Calibration Rake, and Retractable Probe



b. Downstream View

Fig. 2 Concluded



WEDGE HALF-ANGLE (Deg)	δ_n (Deg)	δ_g (Deg)	h (In)	A (In.)	B (In.)	C (In)	D (In.)	E (In.)	F (In)	G (In.)	H (In)
7	700	6 62	0739	5 50	4 50	3.75	3.25	1.75	1.75	2.50	6 13
10	1000	9 68	0727	5.50	4 50	4 25	3.50	2.70	2 50	3 25	5.84
20	2000	19.43	0.473	4.04	3 04	4.56	4 00	2.50	2.50	3.25	7 25

Fig. 3 Pertinent Dimensions of the Pitot-Wedge Calibration Probes

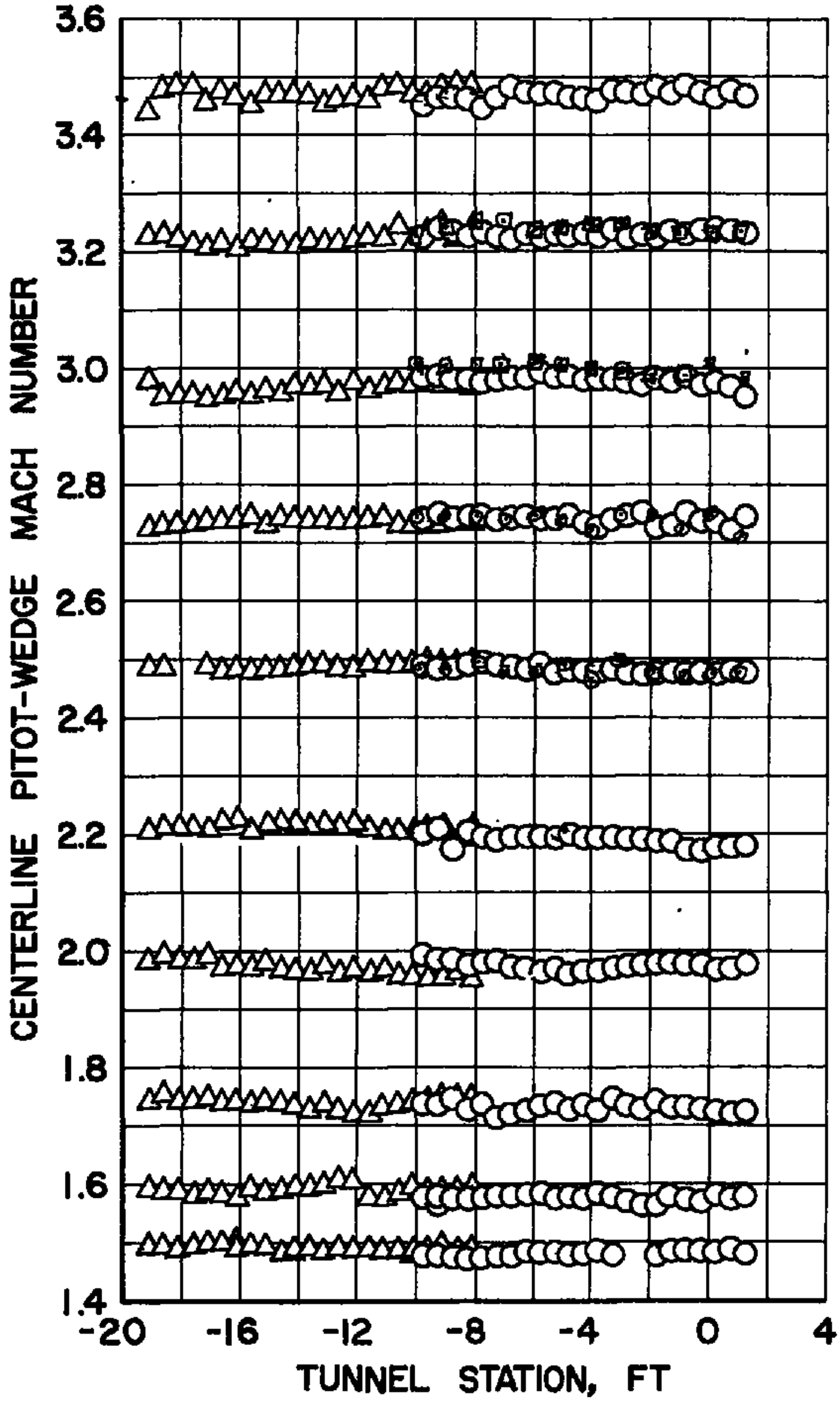


Fig. 4 Mach Number Distributions along the Tunnel Centerline as Determined from Pitot-Wedge Measurements

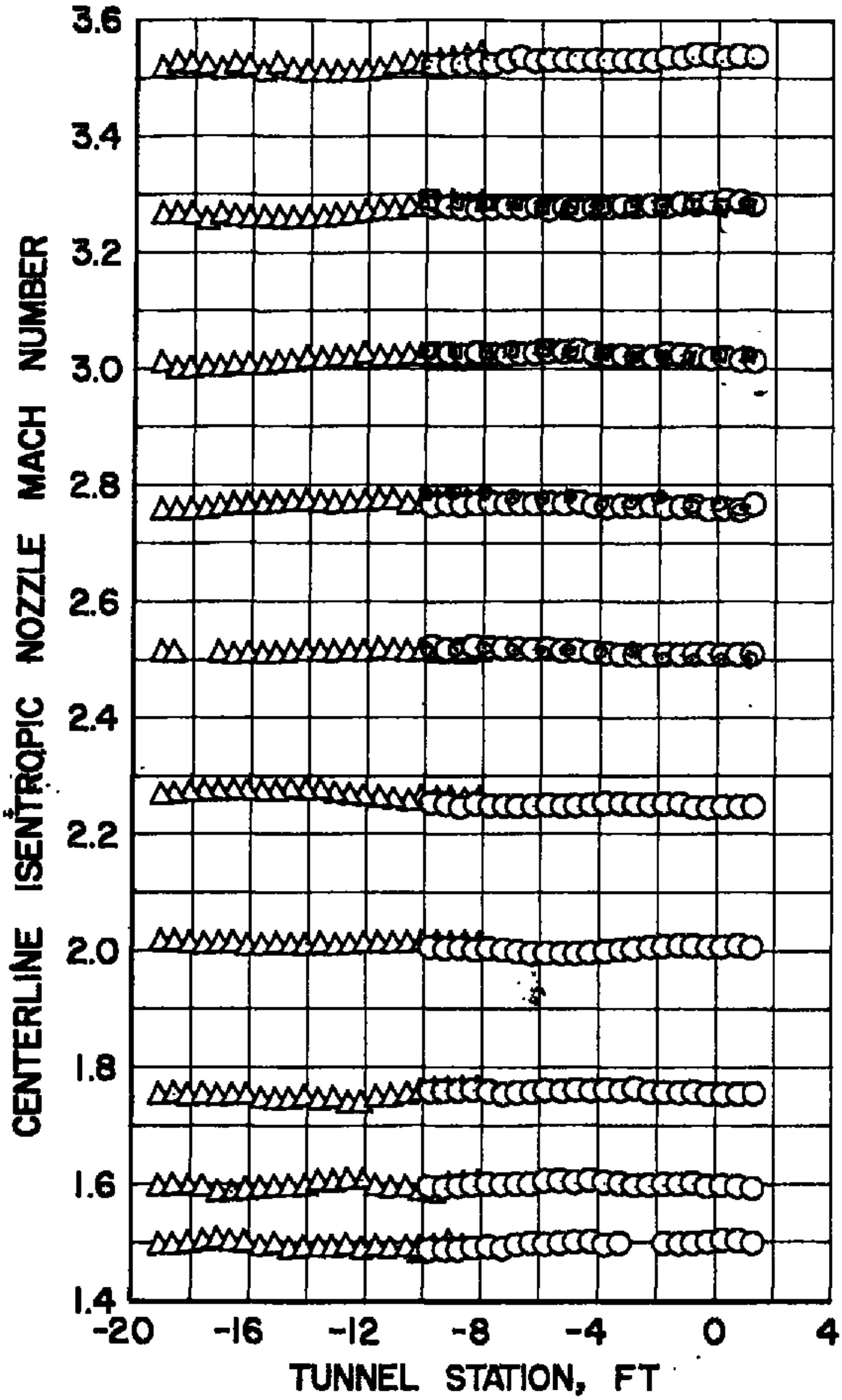
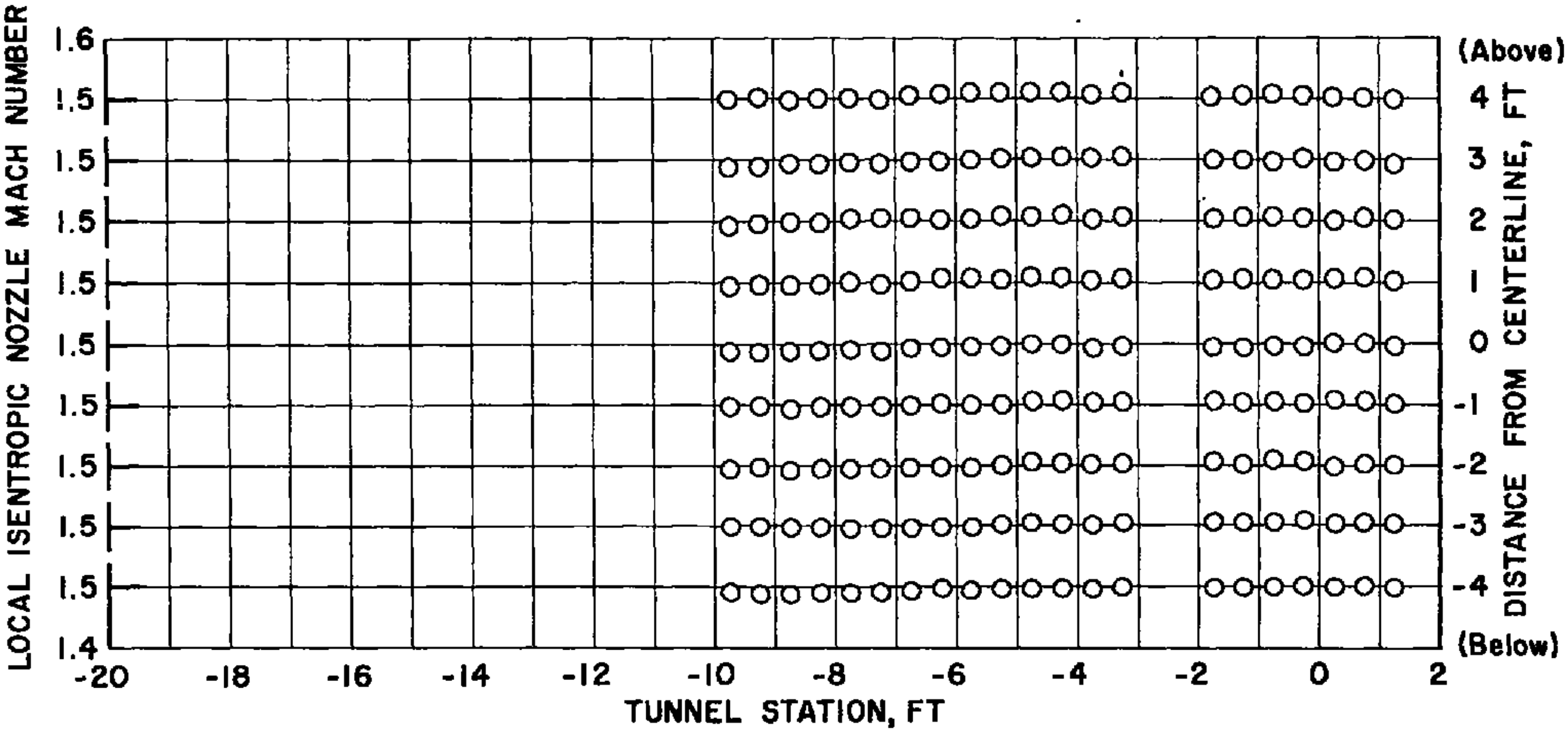
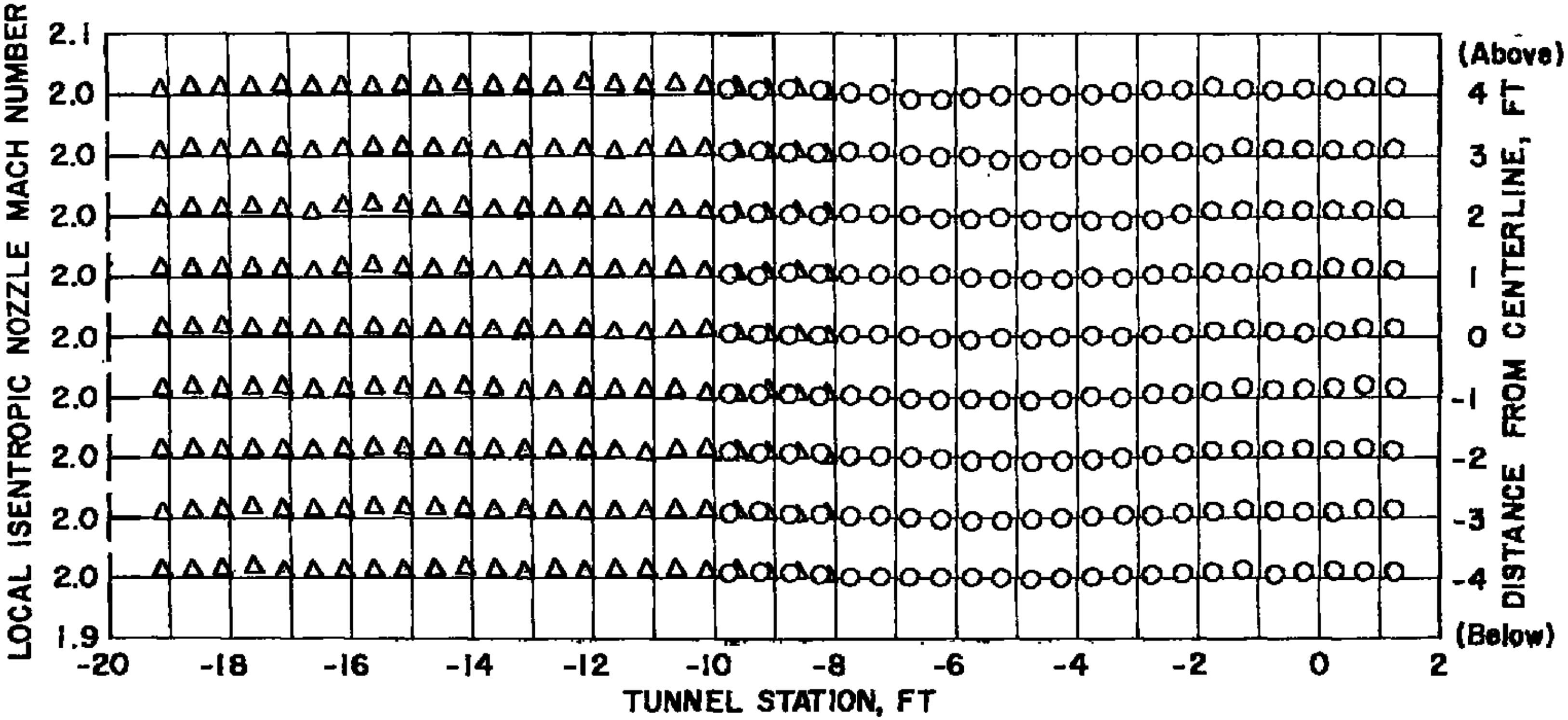


Fig. 5 Centerline Isentropic Mach Number Distributions



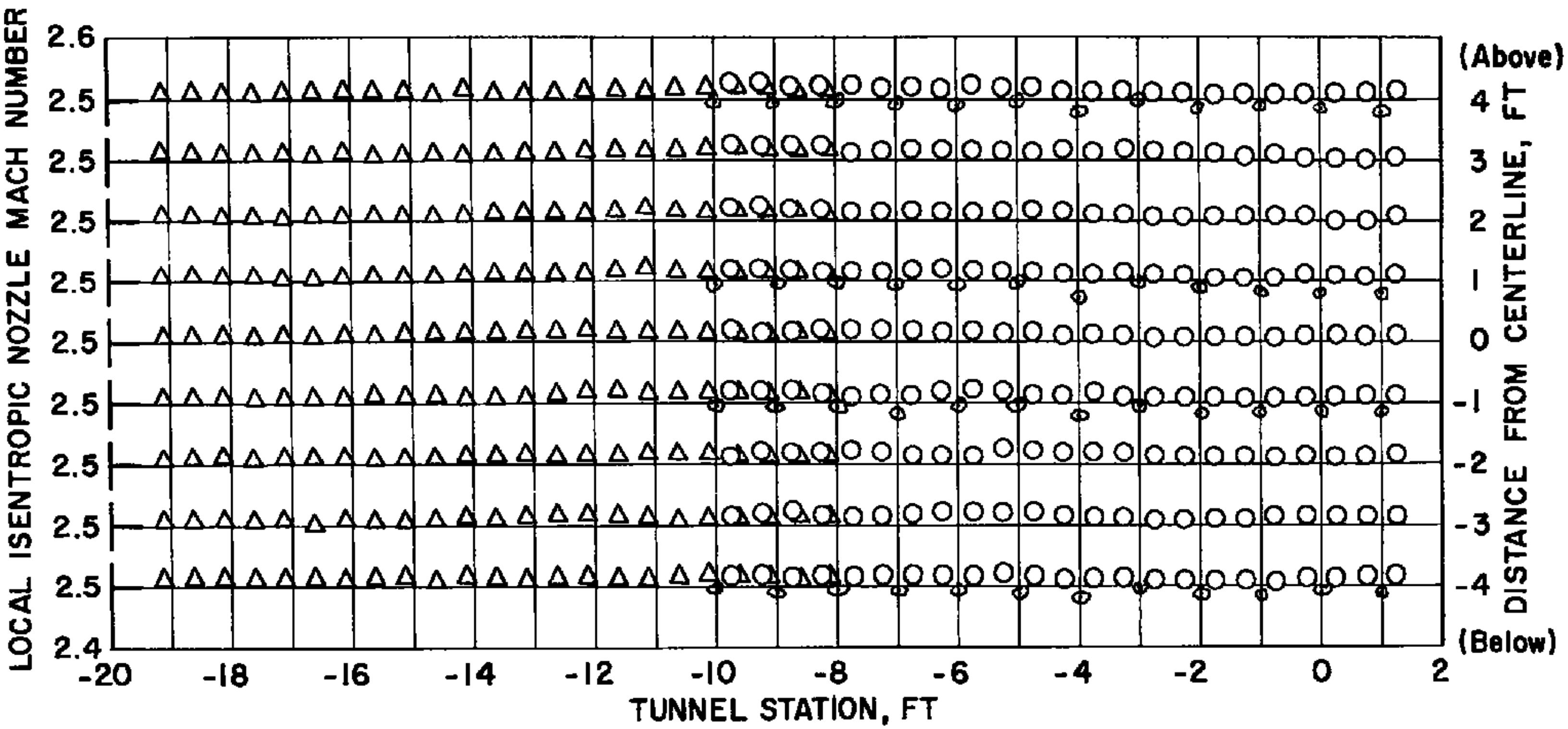
a. $N_M = 1.50$

Fig. 6 Off-Centerline Isentropic Mach Number Distributions in the Vertical Plane



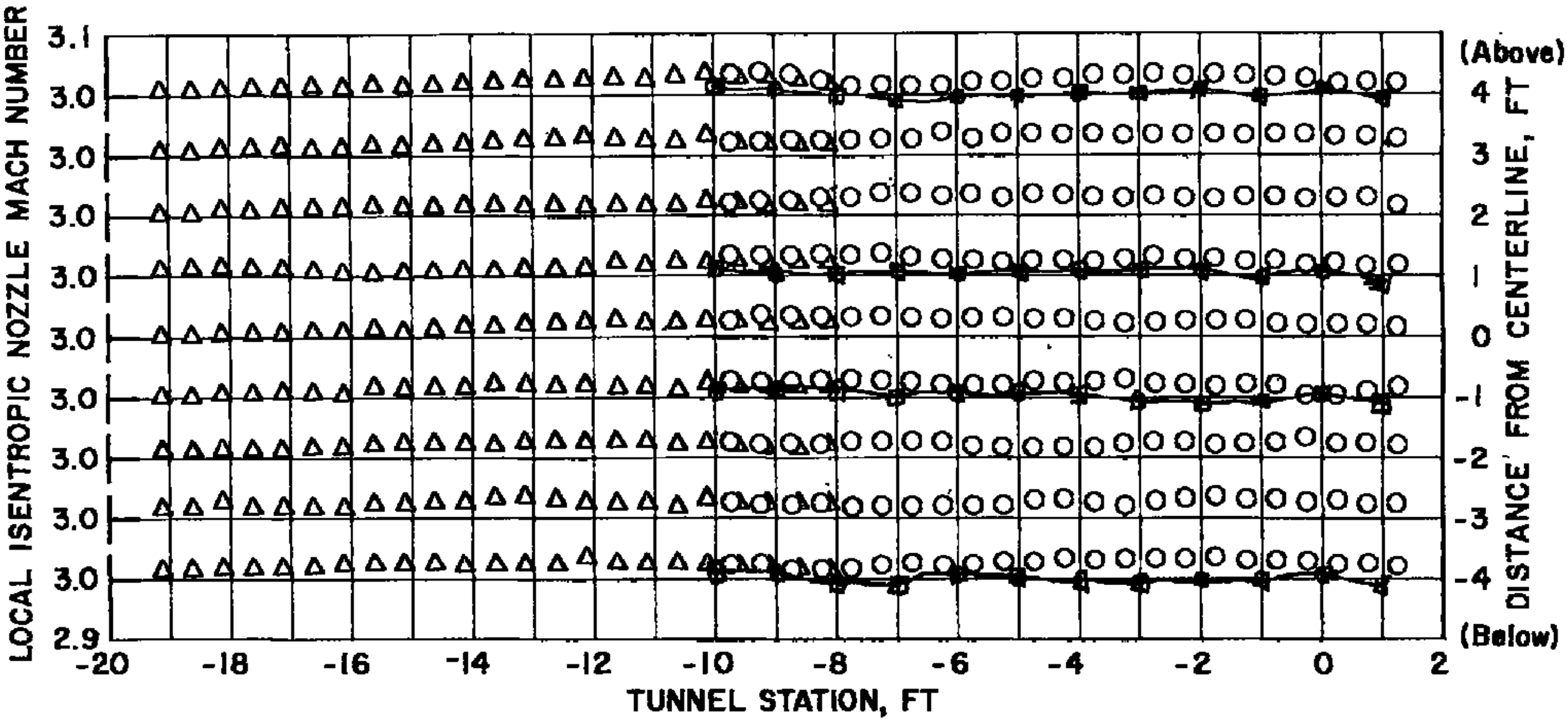
b. N_M = 2.00

Fig. 6 Continued



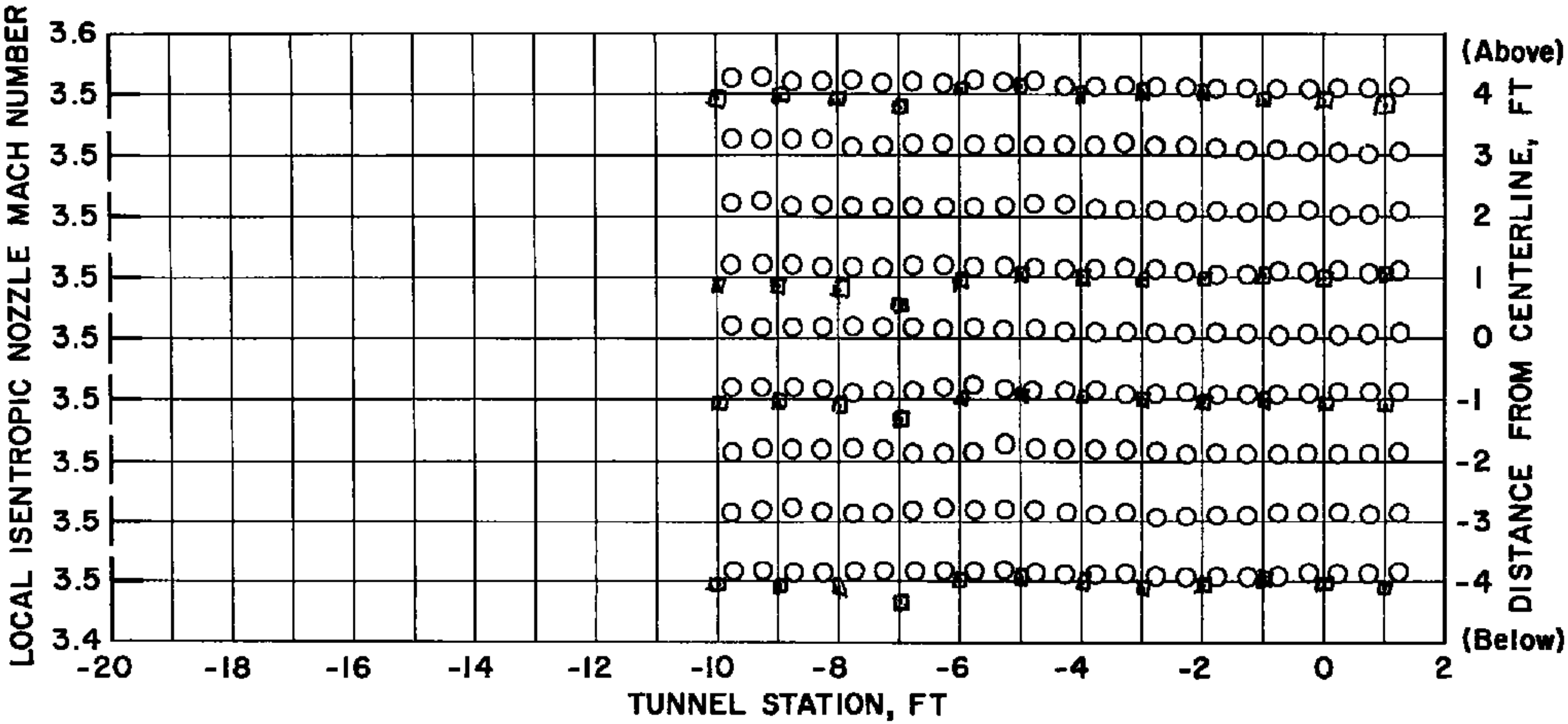
c. $N_M = 2.50$

Fig. 6 Continued



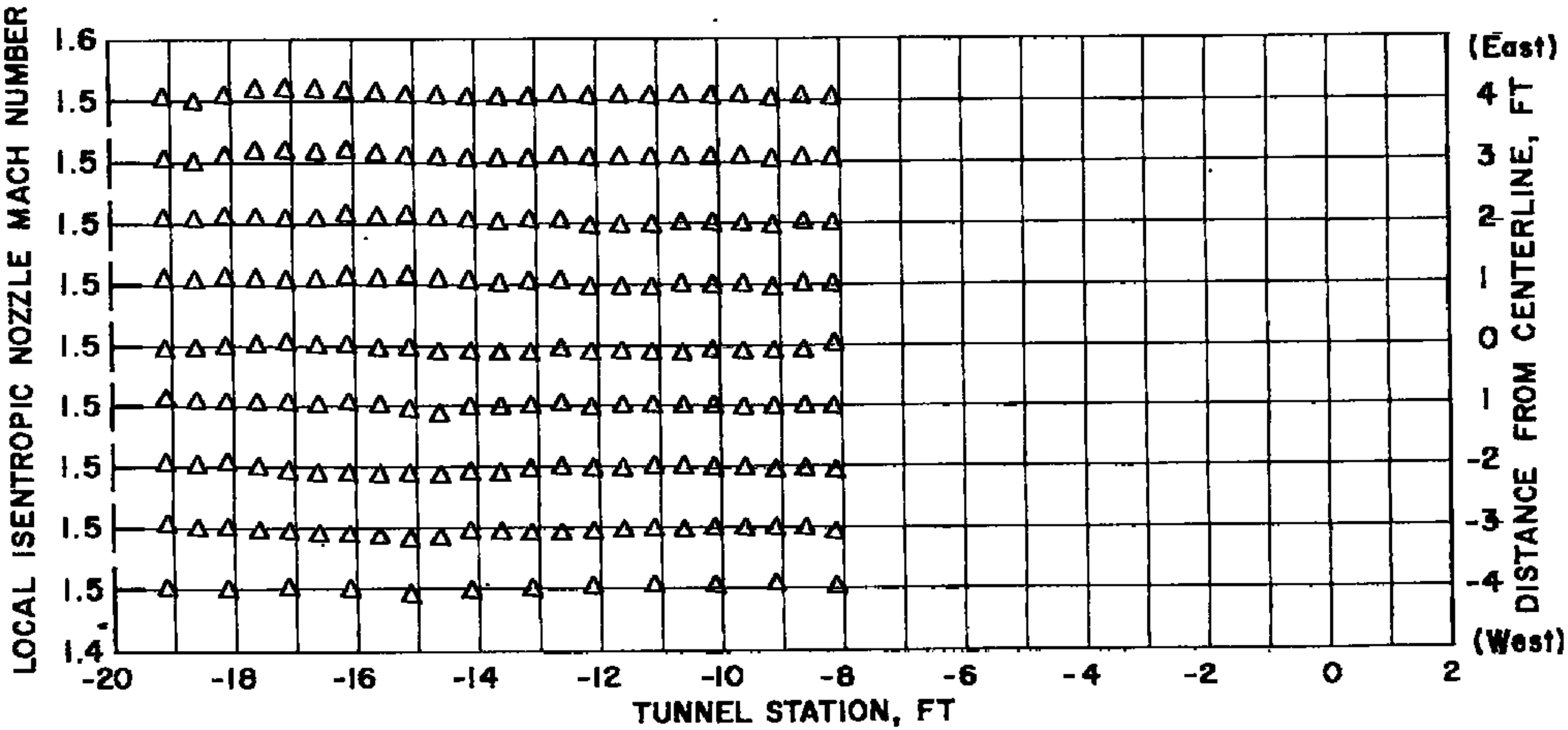
d. $N_M = 3.00$

Fig. 6 Continued



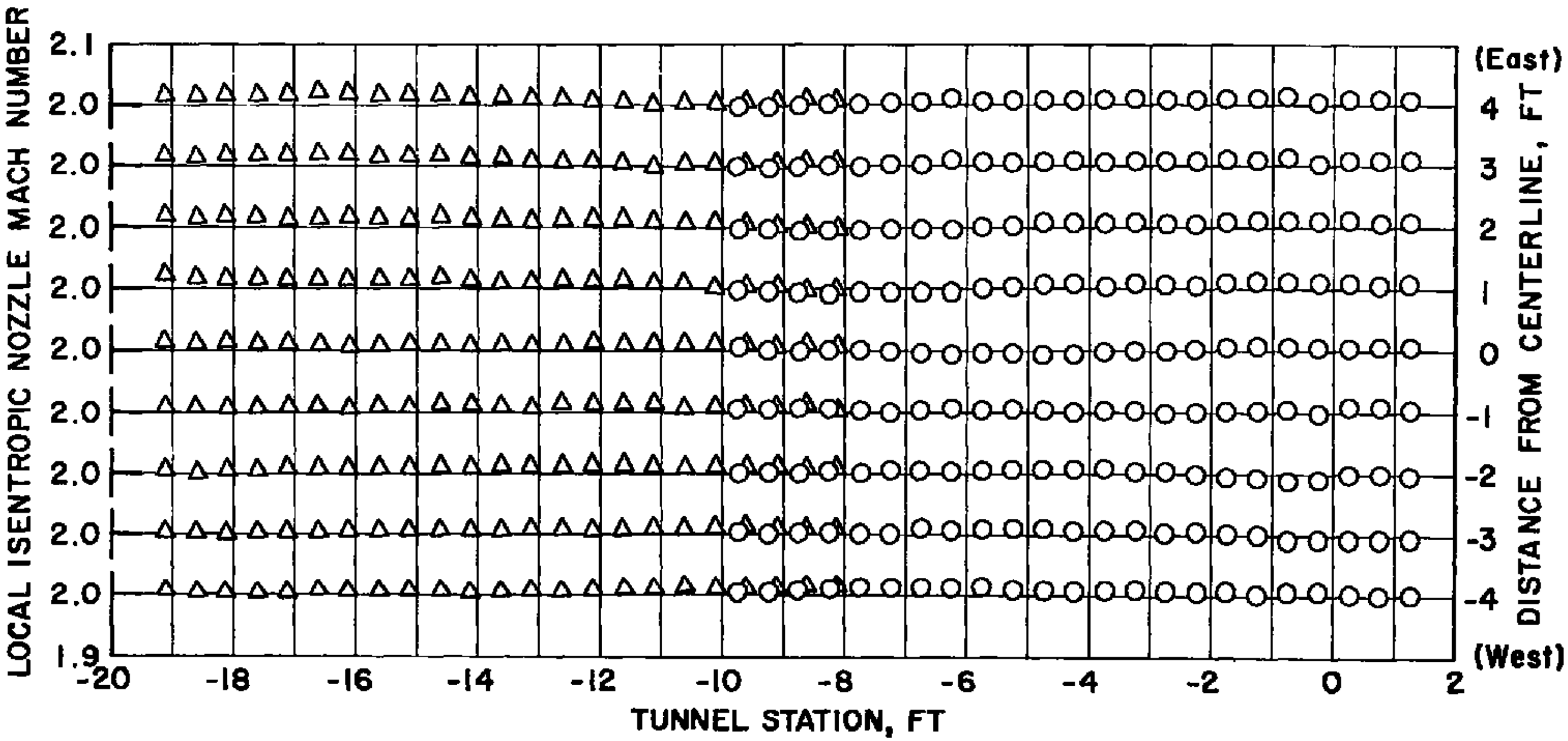
e. N_M = 3.50

Fig. 6 Concluded



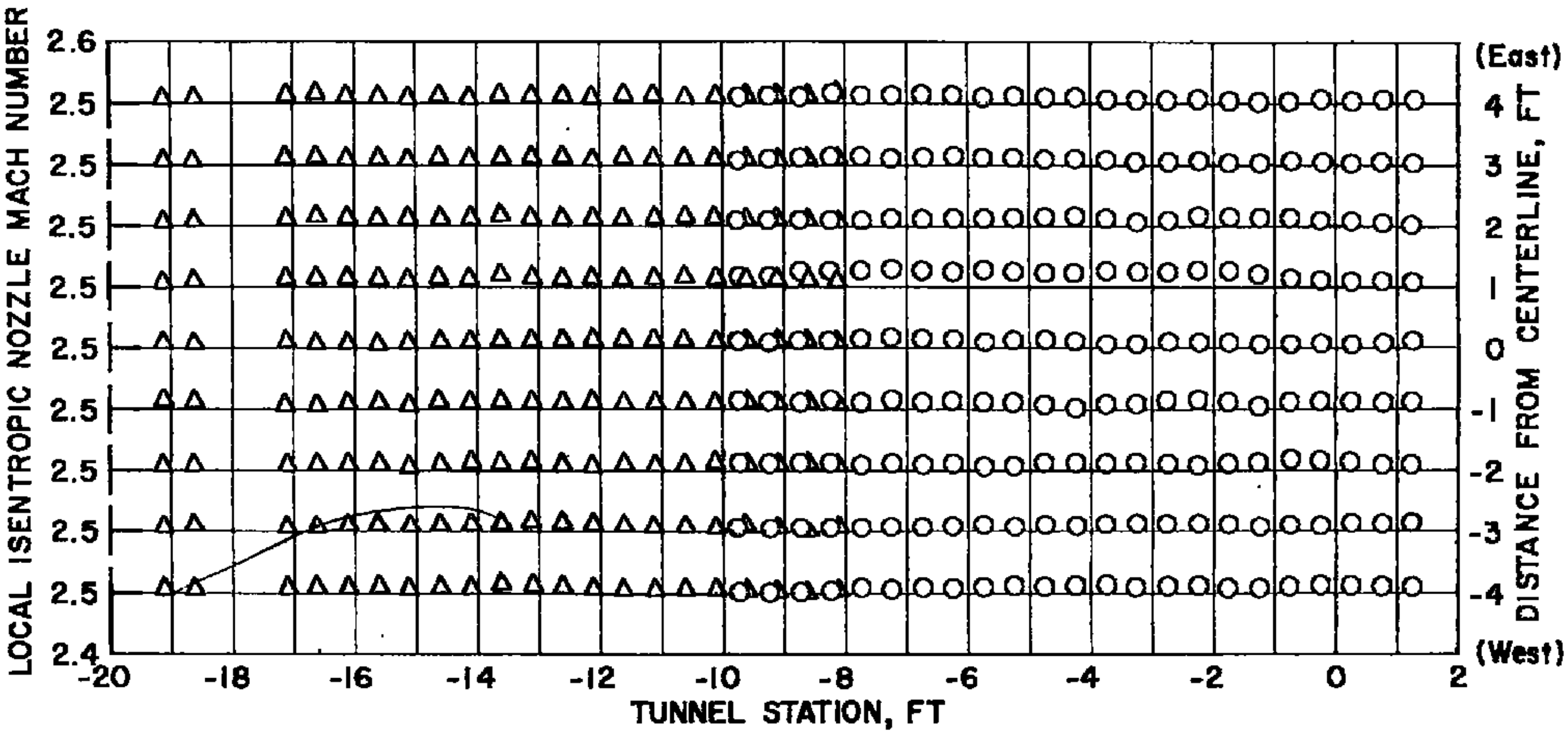
a. $N_M = 1.50$

Fig. 7 Off-Centerline Isentropic Mach Number Distributions in the Horizontal Plane



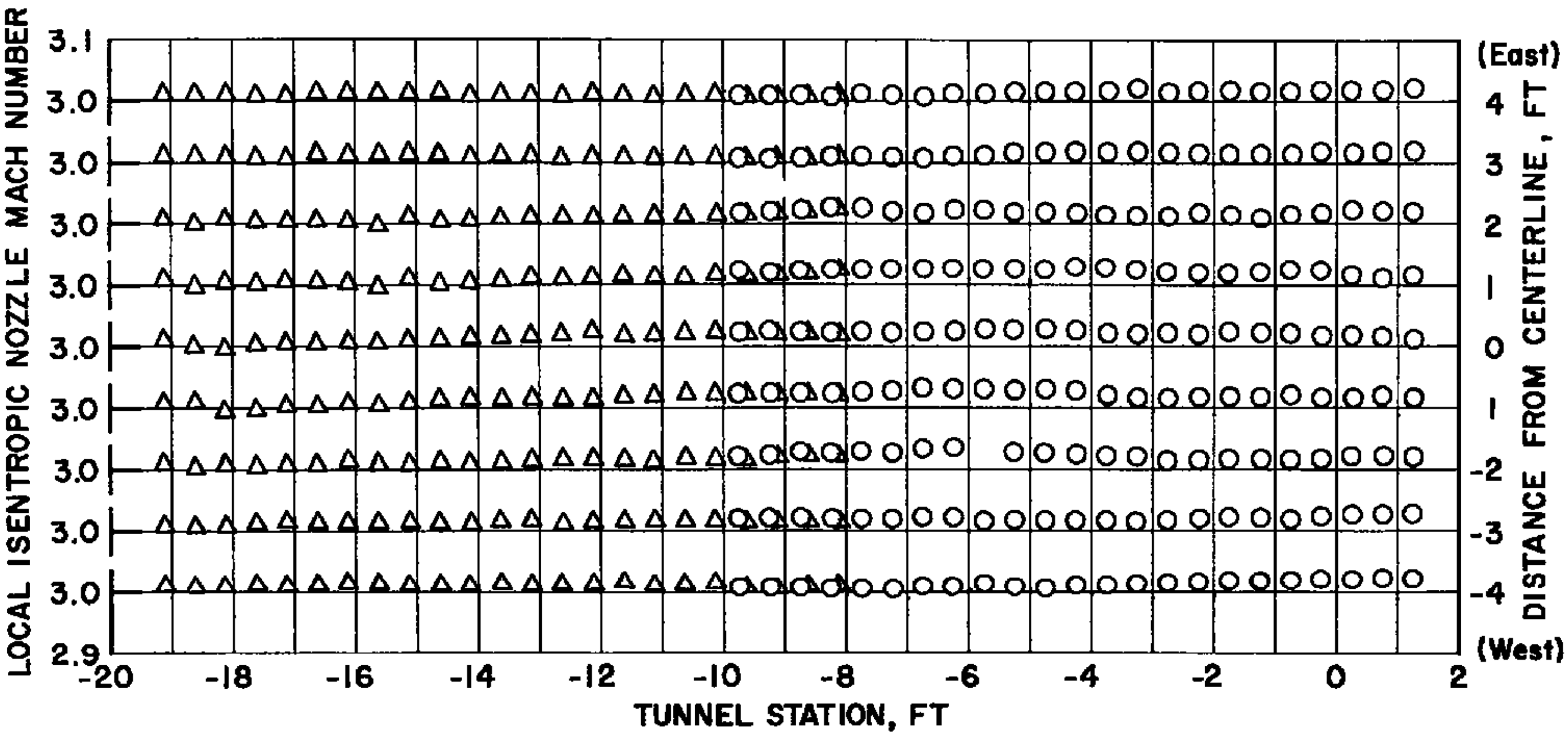
b. N_M = 2.00

Fig. 7 Continued



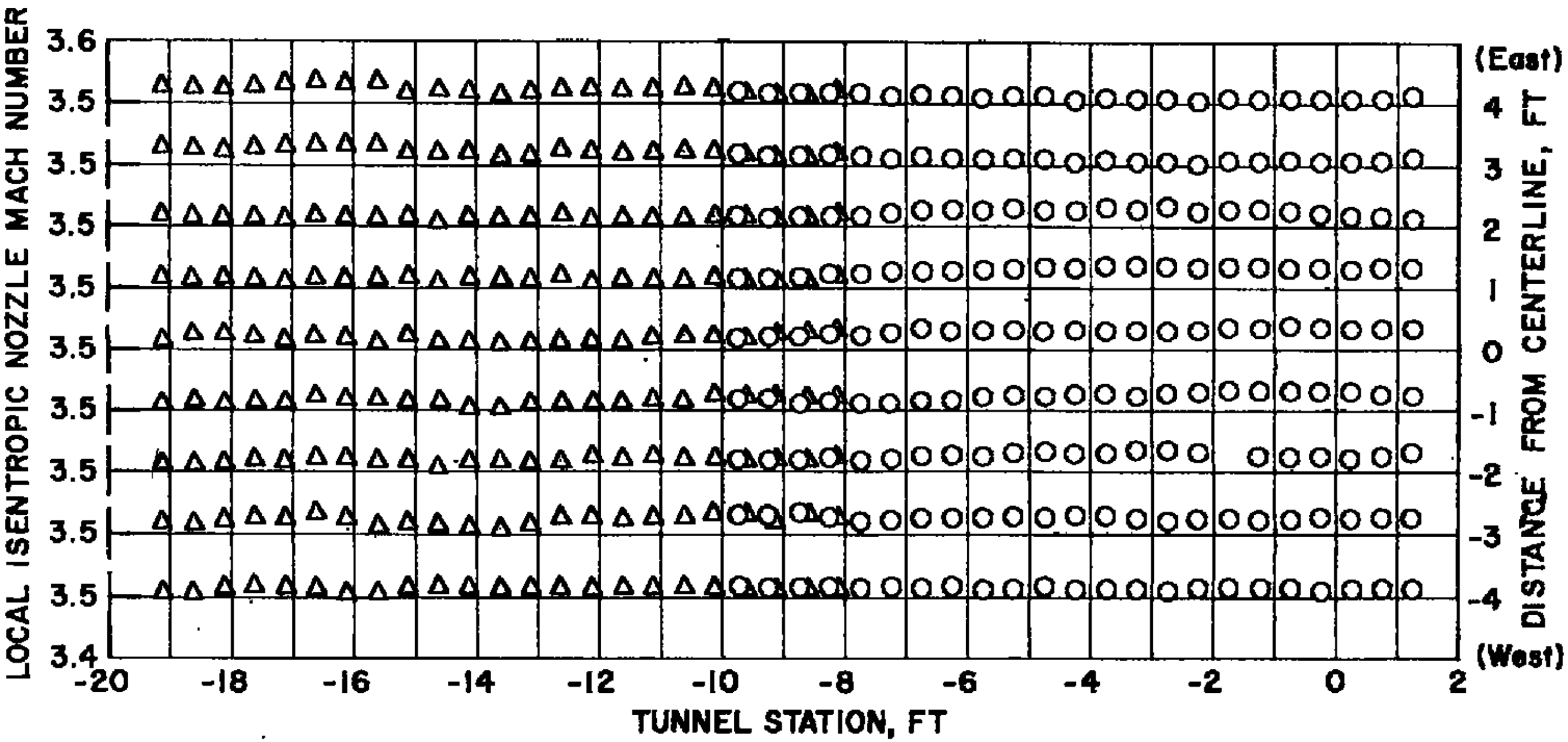
c. $N_M = 2.50$

Fig. 7 Continued



d. N_M = 3.00

Fig. 7 Continued



e. N_M = 3.50

Fig. 7 Concluded

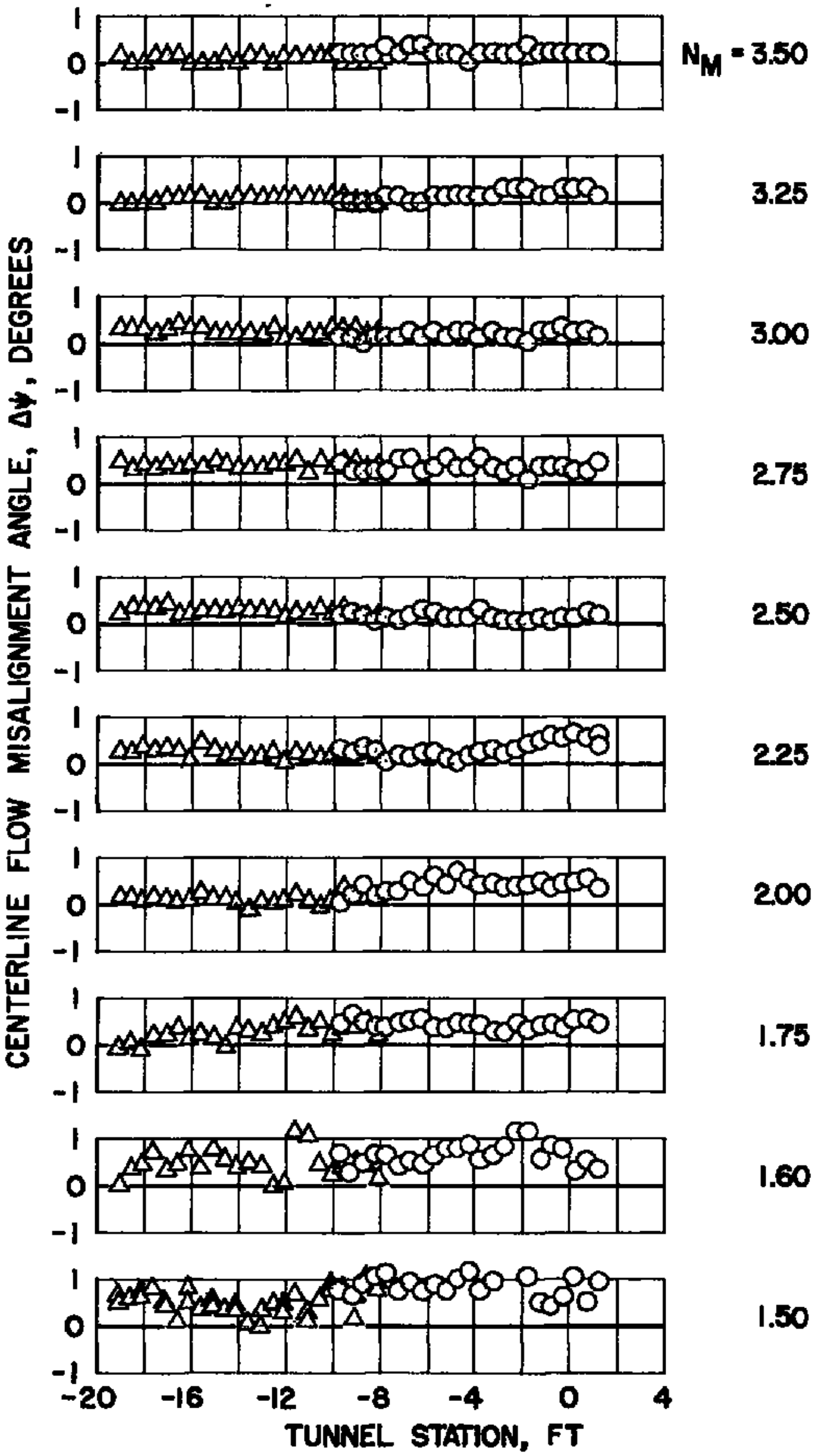
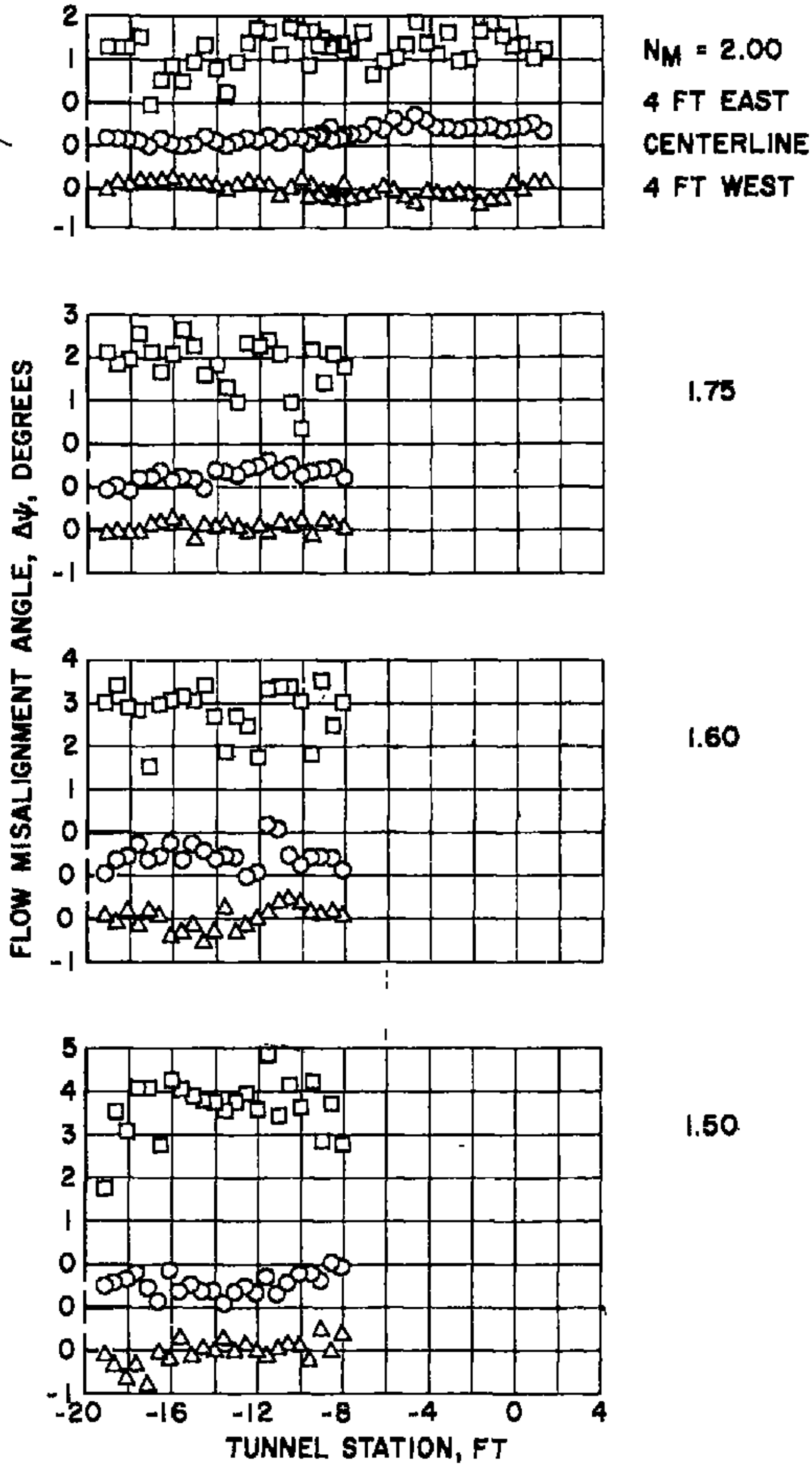
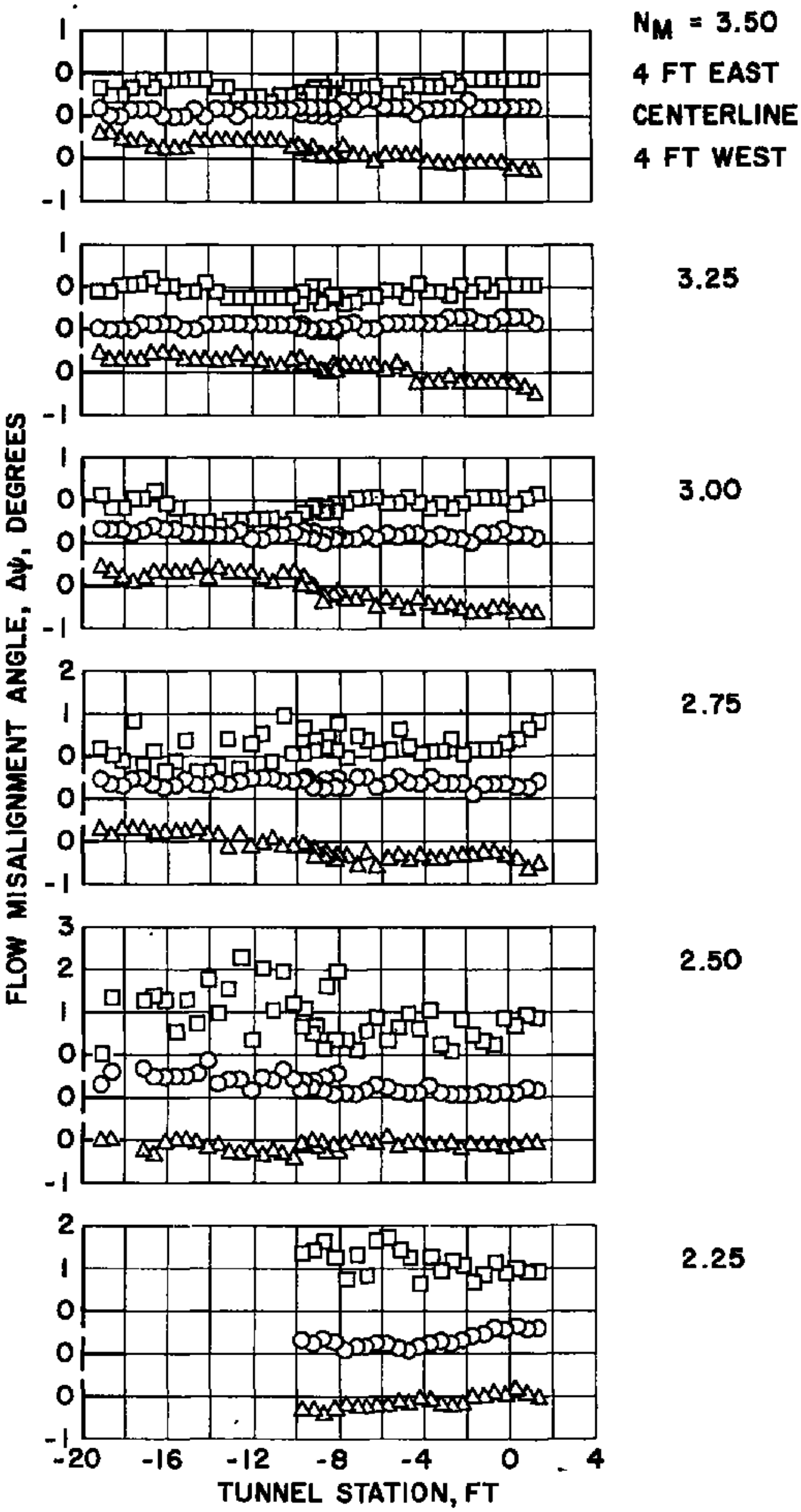


Fig. 8 Lateral Flow Misalignment Measured at the Tunnel Centerline



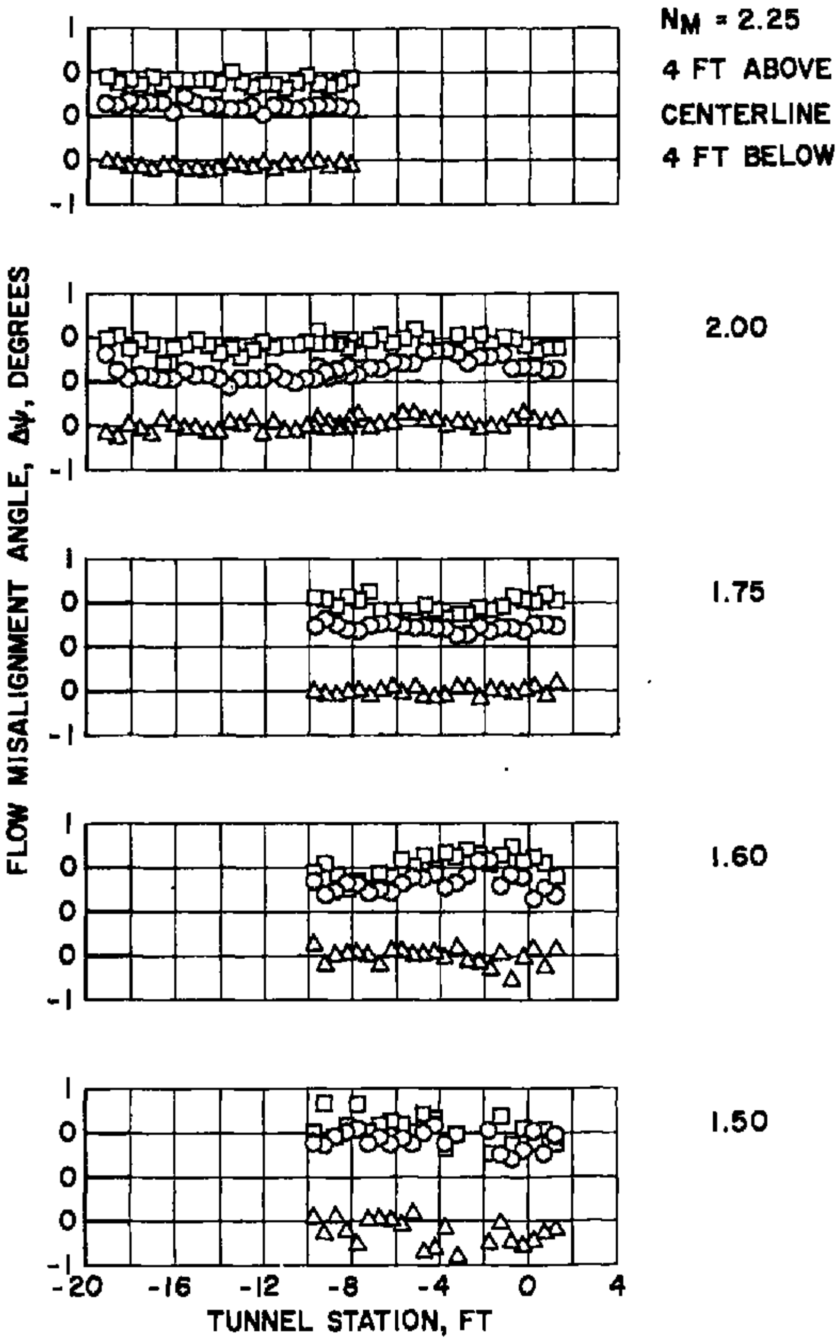
a. East and West of Centerline, N_M = 1.50 to 2.00

Fig. 9 Lateral Flow Misalignment Measured off the Tunnel Centerline



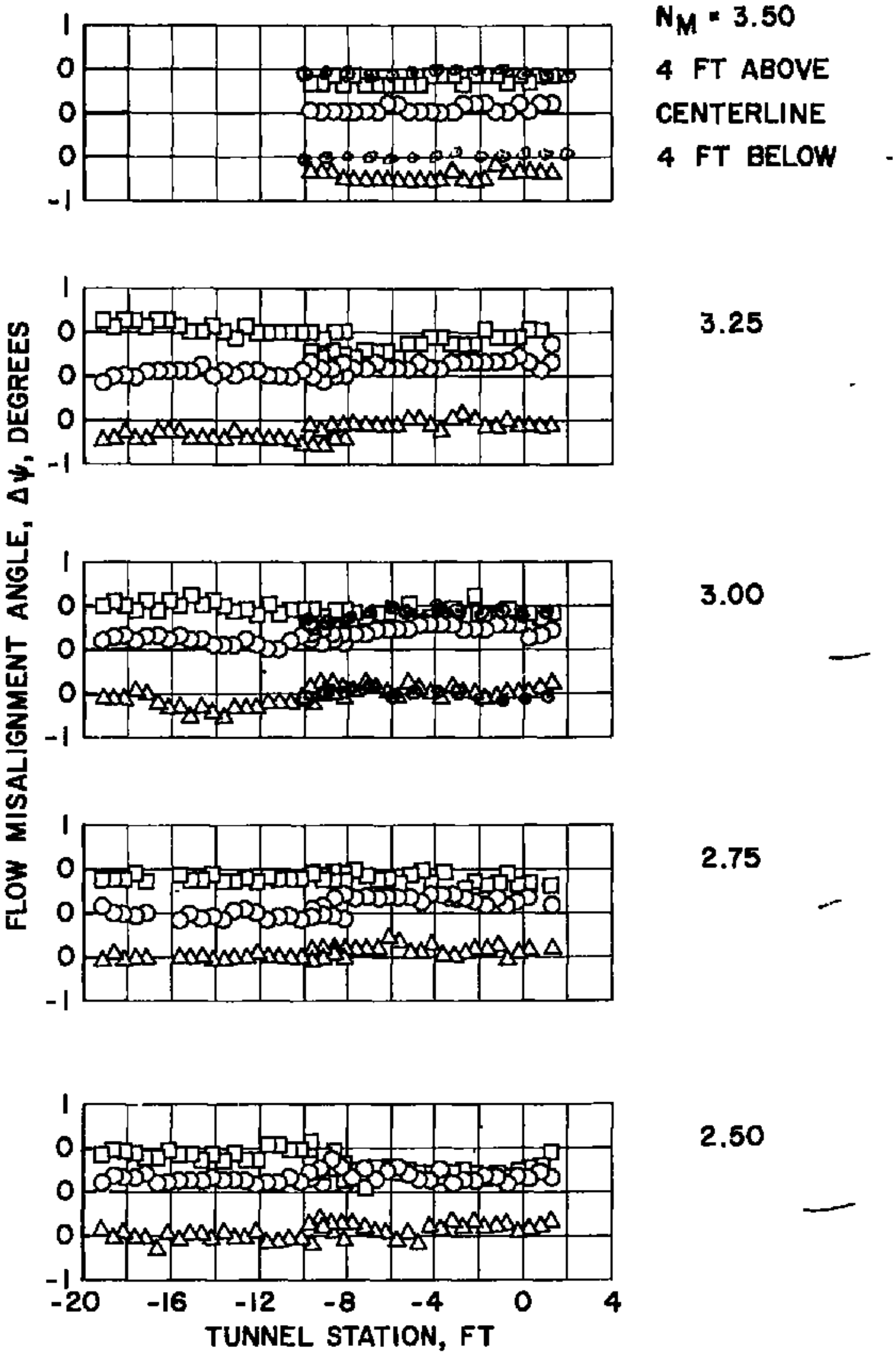
b. East and West of Centerline, N_M = 2.25 to 3.50

Fig. 9 Continued



c. Above and Below Centerline, N_M = 1.50 to 2.25

Fig. 9 Continued



d. Above and Below Centerline, N_M = 2.50 to 3.50

Fig. 9 Concluded

SYMBOL	PROBE POSITION	RAKE ORIENTATION	TEMPERATURE RANGE
○	REAR	VERTICAL	NORMAL
□	REAR	VERTICAL	HOT
◇	REAR	HORIZONTAL	NORMAL
△	FORWARD	HORIZONTAL	NORMAL
◺	FORWARD	VERTICAL	NORMAL

PITOT-WEDGE PROBE HALF-ANGLE	7 DEG.	10 DEG.	20 DEG.
SYMBOL TYPE	○	◑	●

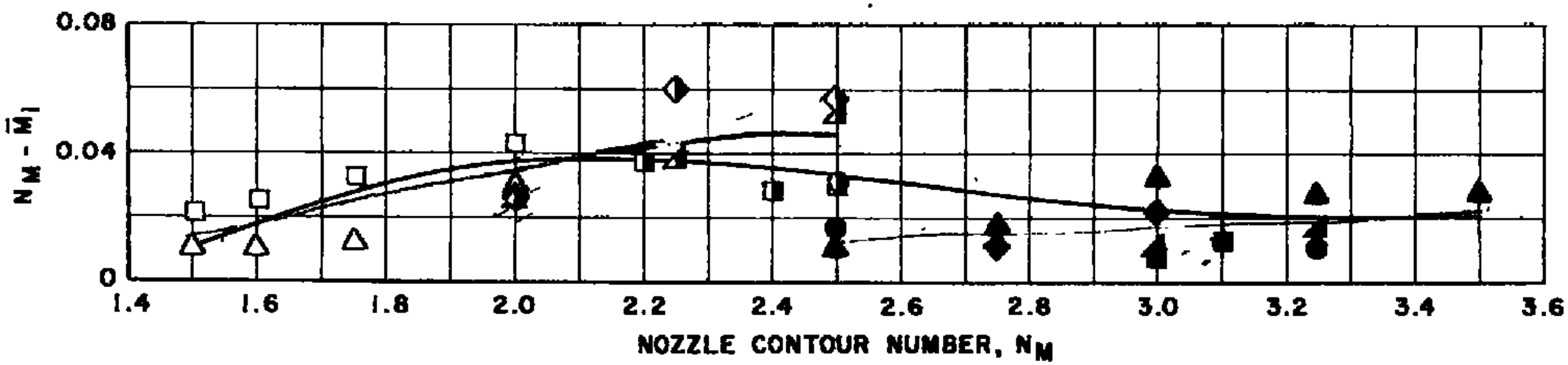


Fig. 10 Variation of the Nozzle Calibration Parameter $N_M - \bar{M}_I$ with Nozzle Contour Number

SYMBOL	PROBE POSITION	RAKE ORIENTATION	TEMPERATURE RANGE
○	REAR	VERTICAL	NORMAL
□	REAR	VERTICAL	HOT
◇	REAR	HORIZONTAL	NORMAL
△	FORWARD	HORIZONTAL	NORMAL
◺	FORWARD	VERTICAL	NORMAL

PITOT-WEDGE PROBE HALF-ANGLE	7 DEG.	10 DEG.	20 DEG.
SYMBOL TYPE	○	◑	●

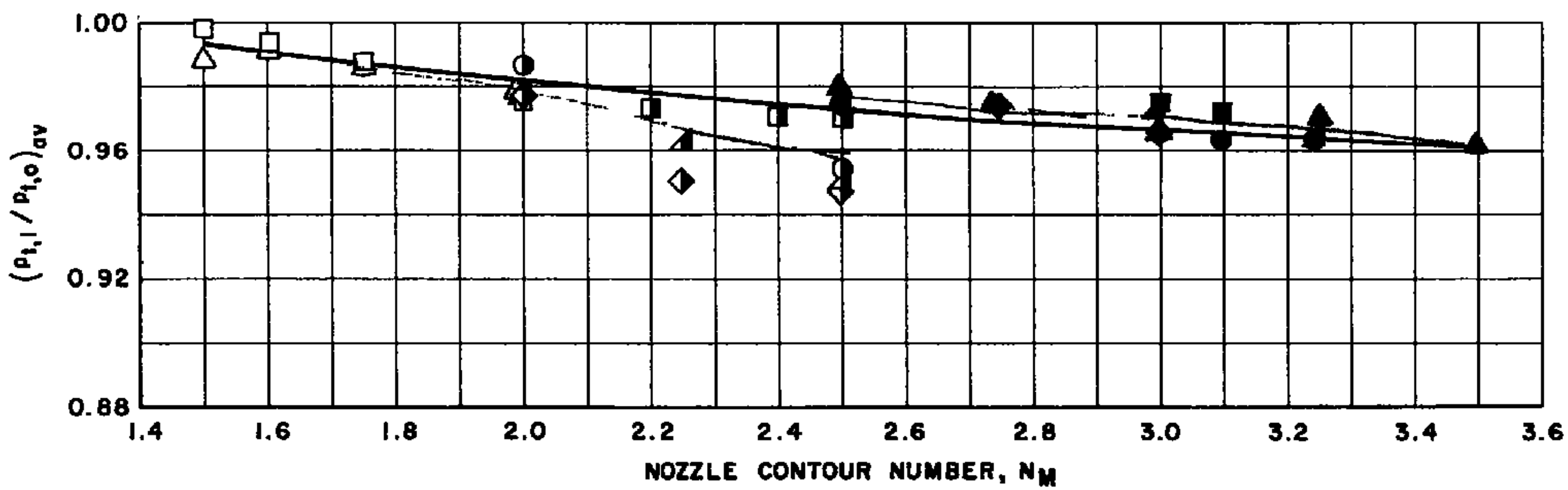


Fig. 11 Variation of Nozzle Pressure Recovery with Nozzle Contour Number

SYMBOL	PROBE POSITION	RAKE ORIENTATION	TEMPERATURE RANGE
○	REAR	VERTICAL	NORMAL
□	REAR	VERTICAL	HOT
◇	REAR	HORIZONTAL	NORMAL
△	FORWARD	HORIZONTAL	NORMAL
◺	FORWARD	VERTICAL	NORMAL

PITOT-WEDGE PROBE HALF-ANGLE	7 DEG.	10 DEG.	20 DEG.
SYMBOL TYPE	○	◑	●

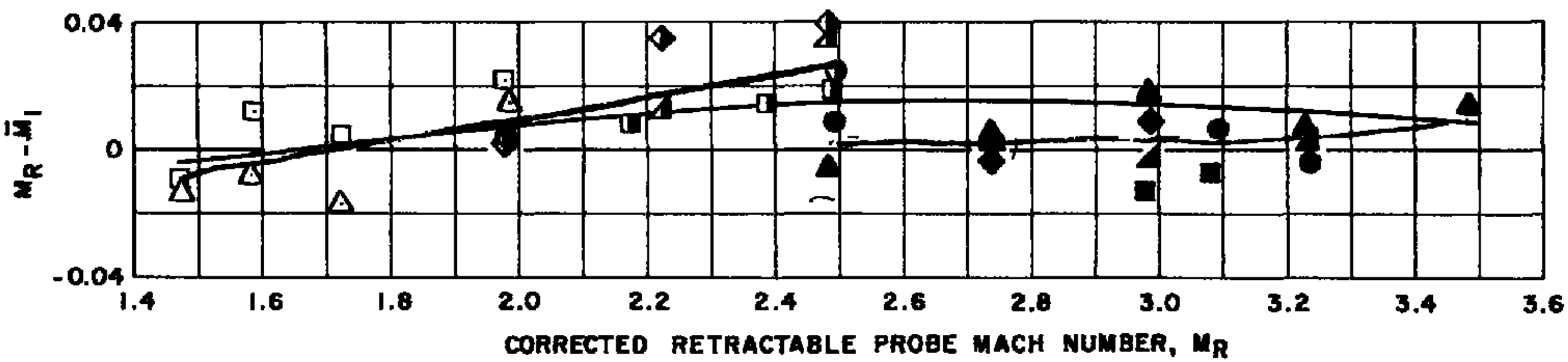


Fig. 12 Variation of the Retractable Probe Calibration Parameter $M_R - \bar{M}_I$ with Mach Number

SYMBOL	PROBE POSITION	RAKE ORIENTATION	TEMPERATURE RANGE
○	REAR	VERTICAL	NORMAL
□	REAR	VERTICAL	HOT
◇	REAR	HORIZONTAL	NORMAL
△	FORWARD	HORIZONTAL	NORMAL
◺	FORWARD	VERTICAL	NORMAL

PITOT-WEDGE PROBE HALF-ANGLE	7 DEG.	10 DEG.	20 DEG.
SYMBOL TYPE	○	◑	●

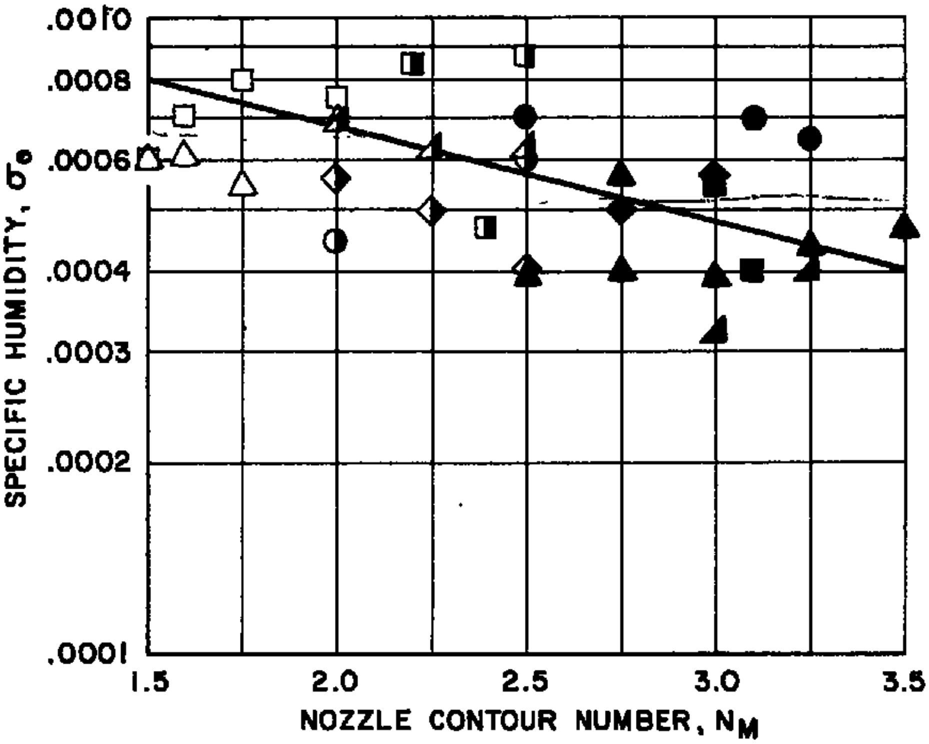


Fig. 13 Variation of Specific Humidity with Nozzle Contour Number during Calibration

SYMBOL	PROBE POSITION	RAKE ORIENTATION	TEMPERATURE RANGE
○	REAR	VERTICAL	NORMAL
□	REAR	VERTICAL	HOT
◇	REAR	HORIZONTAL	NORMAL
△	FORWARD	HORIZONTAL	NORMAL
⊿	FORWARD	VERTICAL	NORMAL

PITOT-WEDGE PROBE HALF-ANGLE	7 DEG.	10 DEG.	20 DEG.
SYMBOL TYPE	○	◑	●

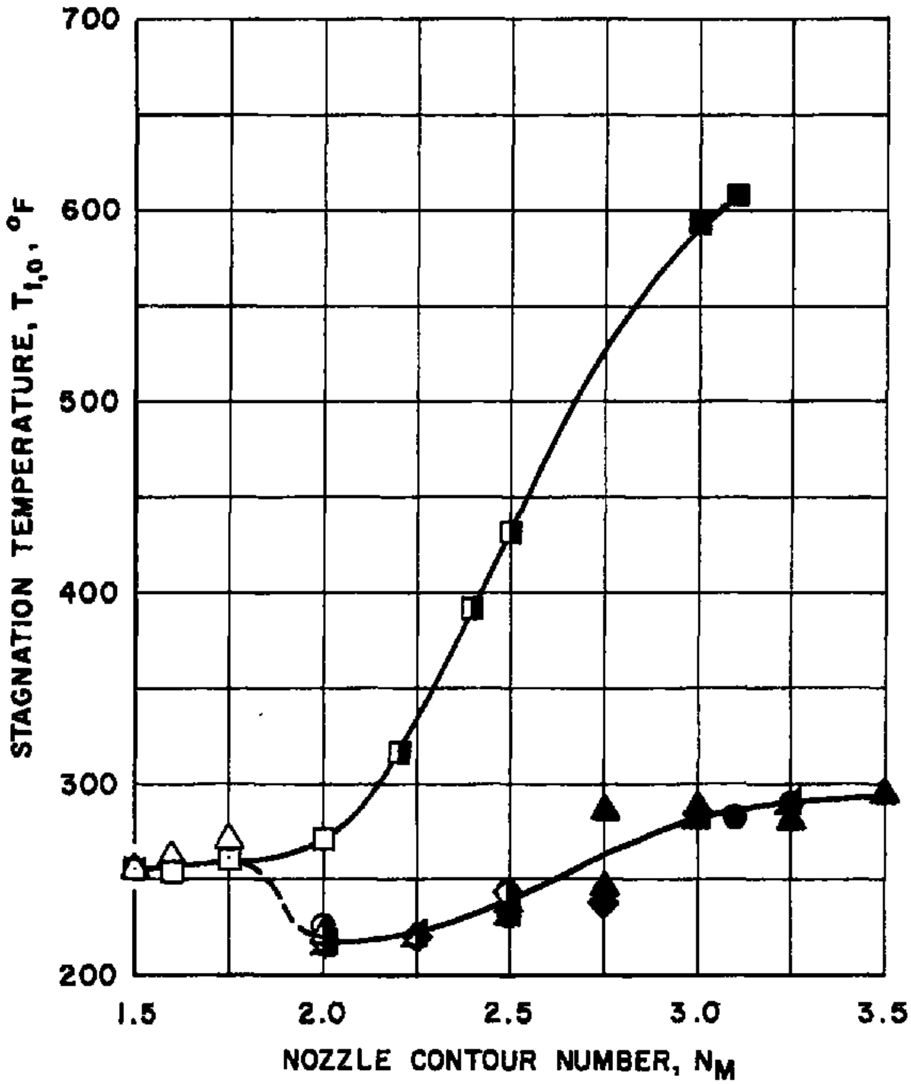


Fig. 14 Variation of Stagnation Temperature with Nozzle Contour Number during Calibration

SYMBOL	PROBE POSITION	RAKE ORIENTATION	TEMPERATURE RANGE
○	REAR	VERTICAL	NORMAL
□	REAR	VERTICAL	HOT
◇	REAR	HORIZONTAL	NORMAL
△	FORWARD	HORIZONTAL	NORMAL
◺	FORWARD	VERTICAL	NORMAL

PITOT-WEDGE PROBE HALF-ANGLE	7 DEG.	10 DEG.	20 DEG.
SYMBOL TYPE	○	◑	●

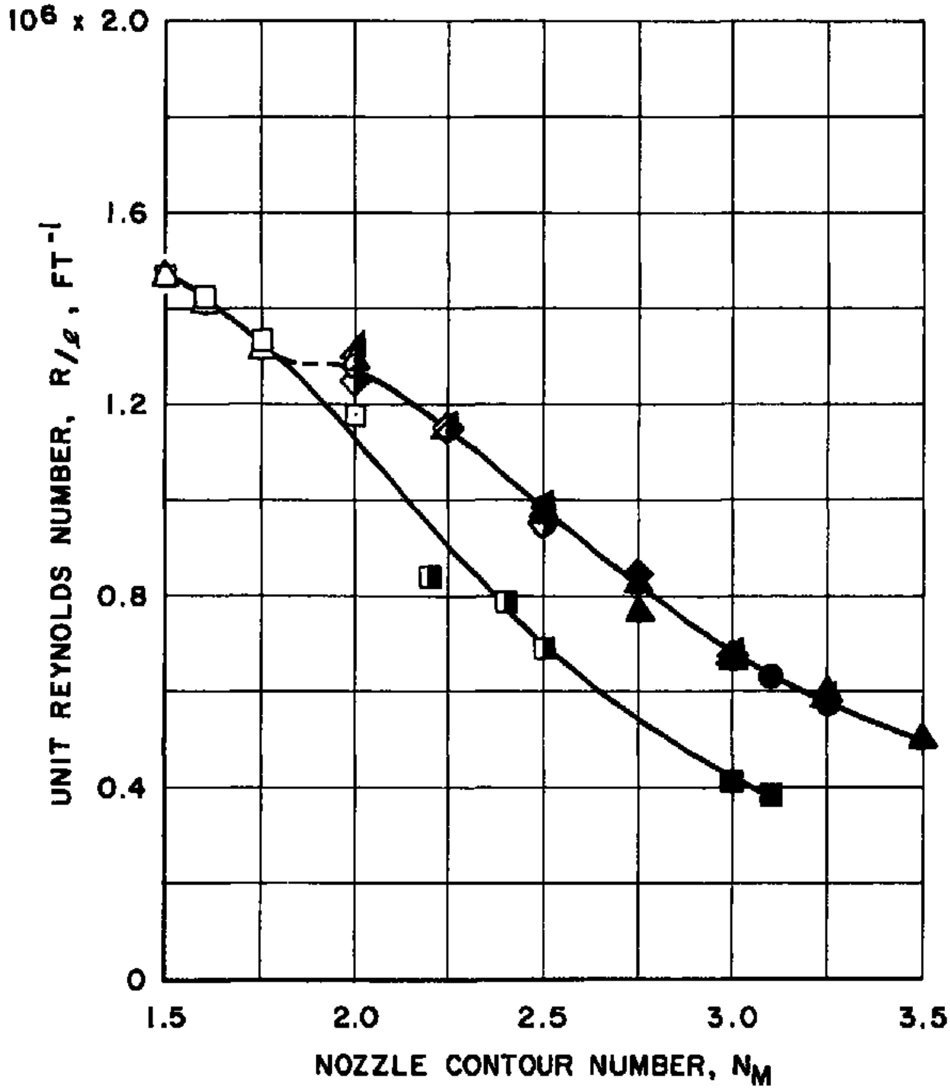


Fig. 15 Variation of Unit Reynolds Number with Nozzle Contour Number during Calibration

Arnold Engineering Development Center
Arnold Air Force Station, Tennessee
Rpt. No. AEDC-TDR-62-55. INITIAL AERODYNAMIC CALIBRATION RESULTS FOR THE AEDC-PWT 16-FT SUPERSONIC TUNNEL (U). March 1962, 53 p. incl 4 refs., illus.

Unclassified Report

Initial aerodynamic calibration of the testing region of the PWT 16-Ft Supersonic Tunnel consisted of surveys of a twenty-foot length of nozzle and test section in which the most desirable model locations occur. These surveys were obtained with an eight-foot traversing rake utilizing pitot-wedge and pitot-temperature probes. The data obtained from these surveys included isentropic-nozzle Mach number distributions both on and off the centerline, true local Mach number determined from the pitot-wedge probes, nozzle pressure recovery, and flow misalignment. These surveys were conducted at nozzle Mach numbers of 1.50, 1.60, 1.75, 2.00, 2.25, 2.50, 2.75, 3.00, 3.25, and 3.50. Results show that maximum Mach number variations over the surveyed length are ±0.02. The stagnation pressure recovery through the nozzle, for the range of specific humidity obtained during this program, varied from 0.993 at N_m = 1.50 to 0.961 at N_m = 3.50.

1. Supersonic wind tunnels
2. Calibration
3. Mach number
4. Pressure
5. Supersonic flow
6. Measurement

I. Contract AF 40(600)-800 S/A 24(61-73)
II. ARO, Inc., Arnold AF Sta, Tenn.
III. Nichols, J. H., Davis, M. W., and Garner, C. L., Jr.
IV. Available from OTS
V. In ASTIA collection

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